Application of 3D scanning technology in forensic investigation of bite-marks

By

Mithun Rajshekar

BDS, MFSc

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Supervisors

The research work presented in this thesis was supervised by

Primary supervisor

Assoc Prof Roberta Julian

Tasmanian Institute of Law Enforcement

Studies

University of Tasmania

Hobart

Primary supervisor

Assoc Prof Leigh Blizzard

Senior Biostatistician

Menzies Institute for Medical Research

University of Tasmania

Hobart

Research Advisor

Assoc Prof Anne-Marie Williams

State Forensic Anthropologist, Tasmania

School of Medicine

University of Tasmania

Hobart

Declaration of originality

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Mithun Rajshekar

Statement of co-authorship

This thesis includes papers for which Mithun Rajshekar (MR) is the first but not the sole author. MR led the work in developing and conceptualising the papers, implementing the analysis and writing the manuscripts under the joint supervision of primary supervisors Leigh Blizzard (LB) and Roberta Julian (RJ) and research advisors Anne-Marie Williams (A-MW), Marc-Tennant (MT), Alex Forrest (AF), Laurence J Walsh (LJW) and Gary Wilson (GW). Throughout the work presented herein, MR was assisted by all listed co-authors. Detailed below are the contributions of MR and each of the co-authors for each paper reported in this thesis.

Paper reported in Chapter 2

Rajshekar M, Blizzard L, Julian R, Williams AM, Tennant M, Forrest A, Walsh LJ, Wilson G. *The incidence of public sector hospitalisations due to dog bites in Australia 2001–2013*. Australian and New Zealand Journal of Public Health. 2017 Aug 1;41(4):377-80.

MR submitted and obtained ethics approval, performed all the data collection, and conducted the statistical analysis under the supervision of LB. MR drafted the manuscript and co-ordinated revisions and submissions to journals.

LB was involved in the initial conceptualization, development and drafting of the study, along with interpretation of the results and manuscript revisions.

RJ was involved in conceptualizing the study and manuscript revisions.

A-MW was involved with conceptualizing the study and manuscript revisions.

MT assisted with manuscript revision.

AF assisted with manuscript revision.

LJW assisted with manuscript revision.

GW assisted with manuscript revision.

Paper reported in Chapter 3

Rajshekar M, Blizzard L, Williams A-M, Tennant M, Forrest A, Walsh LJ, et al. *Bite-mark analysis- a path forward.* 2017: 1-22 (submitted for publication: Australian Journal of Forensic Sciences).

MR conceptualised and drafted the manuscript and co-ordinated revisions and submissions to journals.

LB was involved in the initial conceptualization, development and drafting of the paper, along with interpretation of the results and manuscript revisions.

RJ was involved in conceptualizing the study and manuscript revisions.

A-MW was involved with conceptualizing the study and manuscript revisions.

MT assisted with manuscript revision.

AF assisted with manuscript revision.

LJW assisted with manuscript revision.

GW assisted with manuscript revision.

Paper reported in chapter 4

Rajshekar M, Julian R, Williams AM, Tennant M, Forrest A, Walsh LJ, Wilson G, Blizzard L. *The reliability and validity of measurements of human dental casts made by an intra-oral 3D scanner, with conventional hand-held digital callipers as the comparison measure.* Forensic Science International. 2017 Sep 1;278:198-204.

MR submitted and obtained ethics approval, performed all the data collection, and conducted the statistical analysis under the supervision of LB. MR was responsible for obtaining ethics approval. MR drafted the manuscript and co-ordinated revisions and submissions to journals.

LB was involved in the initial conceptualization, development and drafting of the study, along with interpretation of the results and manuscript revisions.

RJ was involved in conceptualizing the study and manuscript revisions.

A-MW was involved with conceptualizing the study and manuscript revisions.

MT assisted with manuscript revision.

AF assisted with manuscript revision.

LJW assisted with manuscript revision.

GW assisted with manuscript revision.

Paper reported in chapter 5

Rajshekar M, Blizzard L, Williams A-M, Tennant M, Forrest A, Walsh LJ, et al. *Assessing the accuracy of matching 3D images of dog dentitions and their impressions using the Zfx IntraScan intra-oral 3D scanner.* 2017 1-16 (submitted for publication: Journal of Forensic Sciences).

MR performed all the data collection, and conducted the statistical analysis under the supervision of LB. MR drafted the manuscript and co-ordinated revisions and submissions to journals.

LB was involved in the initial conceptualization, development and drafting of the study, along with interpretation of the results and manuscript revisions.

RJ was involved in conceptualizing the study and manuscript revisions.

A-MW was involved with conceptualizing the study and manuscript revisions.

MT assisted with manuscript revision.

AF assisted with manuscript revision.

LJW assisted with manuscript revision.

GW assisted with manuscript revision.

I, the undersigned agree with the above stated contributions for each of the manuscripts contained within this thesis that have been published or submitted for peer-review.

Signature

Statement of ethical conduct

The research associated with this thesis abides by the International and Australian codes on human and animal experimentation, the guidelines by the Australian Governments Office of the Gene Technology Regulator and the rulings of the Safety, Ethics and Institutional BioSafety Committees of the University.

14/11/2017

Signature **Date**

Mithun Rajshekar

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Scientific Presentations arising from this thesis

Oral presentations

Year	Title
2016	A path forward for bite-mark analysis: A response to the 2009 National Academy of Science Report - Australian and New Zealand Society of Criminology (Hobart)
2016	Validating an intra-oral 3D scanner as a tool to be used in bite-mark analysis as a response to the 2009 National Academy of Science Report, Australia New Zealand Forensic Science Society Symposium (Auckland)
2016	Assessing the Reliability of Measurements of Human Dental Casts Using an Intra- oral 3D Scanner, American Academy of Forensic Sciences (Las Vegas)
2014	Forensic Odontology and its scientific validity – Presented at the Tasmanian Institute of Law Enforcement Studies Forensic Studies Forum, Hobart
2013	Compilation, classification and measurement of animal dentitions for use a scientific evidence in bite-mark investigation- Presented at the Tasmanian Health Science HDR student conference, Hobart.

Poster presentations

Year	Title
2015	Assessing the reliability of measurements of human dental casts using a Zfx Intrascan Intra-oral 3D-scanner, Australian Society of Forensic Odontology Symposium, Darwin
2014	Animal dentitions as a tool for forensic investigation of bite-marks – Australia New Zealand Forensic Science Society Symposium, Adelaide
2013	Animal dentitions as a tool for forensic investigation of bite-marks: establishing the extent of the problem of dog bites in Australia, developing new techniques for classifying and evaluating the evidence, and creating a repository of information for identifying perpetrators – Graduate Research Conference, University of Tasmania

Awards resulting from this thesis

Year	**Award**
2016	Graduate Research Conference and Research Travel Scheme Travel grant to participate in the American Academy of Forensic Sciences Conference in Las Vegas
2016	Awarded a travel grant from Australia New Zealand Forensic Science Society to Auckland
2016	Awarded the Henry C Lee Scholarship by American Academy of Forensic Sciences
2014	Awarded an Australia New Zealand Forensic Science Society Travel Award to Adelaide
2013	Awarded an APA Post Graduate Scholarship to commence PhD studies with the Menzies Research Institute/Tasmanian Institute of Law Enforcement Studies, University of Tasmania

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Anecdote

Ms. Andrea Clarke was bitten on her leg by a dog when jogging in Claremont, a suburb in Hobart, Tasmania. The bite resulted in penetration of the skin and bleeding. She identified a five-year-old Jack Russell cross from a photo line-up of dogs from the area, including some known offenders, produced by Glenorchy City Council animal control officers. Action was taken in the Magistrates Court against the owner of the Jack Russell cross but Magistrate Catherine Rheinberger dismissed the charges on the grounds that eyewitness identification was unreliable in cases involving humans, let alone dogs. This is an example of how matching (or failing to match) the dentition of the accused dog to the dog-bite might have resolved an issue resulting in personal angst and community conflict.

Abstract

Forensic investigation of bite-marks on humans has the potential to provide evidence that can be used to identify the perpetrator of a bite. Bite-mark evidence has been used in legal proceedings since 1692 but, recently, bite-mark analysis has been subject to substantial criticism. In the USA, there have now been 24 cases involving human perpetrators in which convictions based on bite-mark analysis have been overturned as a result of DNA evidence, including cases in which the defence experts had testified that the suspect dentitions did not match the bite-marks. The overturn of these convictions and the criticisms that followed have led to calls to halt the use of bite-marks as evidence until its scientific credibility can be established, and even to recommendations to discontinue altogether the use of bite-mark evidence in criminal investigations in the US.

To address the fundamental limitations of bite-mark analysis, the aims of this thesis were to estimate the frequency of occurrence of bites, propose the use of 3D imaging technology as an approach to overcome limitations of current methods of bite-mark analysis, investigate the reliability and validity of measurements of landmark dental features made using 3D imaging, and examine the accuracy of matching 3D images of bite-marks to 3D images of candidate dentitions.

This thesis is made up of four key studies. They are summarized below:

Study 1

An important first step was to undertake an assessment of the public health implications of bites inflicted on humans by estimating the frequency of occurrence of the injuries and deaths caused. For information on bites perpetrated by humans on humans, searches and data requests were made on public access information websites and of the Australian Institute of Health and Welfare (AIHW) respectively. The AIHW was unable to provide age and sex specific information on bites caused by humans on other humans. The author’s investigations revealed that there is incomplete and fragmented information on bites perpetrated by humans on humans most commonly in cases of sexual assault and child abuse. Instead the author turned their attention to bites perpetrated by other biting animals, and specifically by dogs because dog-bites are the most common. To determine the extent of the problem, the incidence of public sector hospitalizations resulting from dog-bite related injuries in Australia during the period

2001-2013 was estimated. The principal finding was that on average, 2061 persons were hospitalized each year during that period for treatment for dog-bite injuries at an annual rate of 12.39 (95% CI 12.25, 12.53) per 100,000. The highest annual rates of 25.95 (95% CI 25.16, 26.72) and 18.42 (95% CI 17.75, 19.07) per 100,000 were for age groups 0-4 years and 5-9 years respectively. Rates of recorded events increased over the study period and reached 16.15 (95% CI 15.78, 16.52) per 100,000 during 2011-13. This study was the first national study to report the incidence of hospitalization for injuries due to dog-bites for an extended period with complete coverage of all public hospitals in Australian states and territories. The findings add considerably to what is known about the public health problem of dog-bite injuries in Australia.

Study 2

Recently, the scientific basis of bite-mark analysis has been questioned. The most robust of those criticisms came from the National Academy of Science (NAS). In its report published in 2009, the NAS identified three fundamental limitations of bite-mark analysis. These were that the uniqueness of human dentitions was yet to be determined, that the ability of the human skin to retain faithfully the impression of the biting dentition was yet to be ascertained, and that comprehensive steps to minimise and quantify all other sources of error in matching a bite-mark to a suspect dentition were yet to be undertaken.

To address these fundamental limitations, the author recommends the use of 3D imaging techniques in bite-mark analysis. The new generation of portable, non-invasive, hand-held intra-oral 3D scanners, that are currently used as an alternative to conventional dental impression materials in clinical dentistry, have made the process of acquiring dental impressions faster and easier. The 3D scanning permits the imaging of bite-marks as well as the imaging of biting dentitions of suspected perpetrators in 3 dimensions with high resolution, and would allow researchers to compile large databases of virtual images of dentitions of biting animals for quantifying population variation. In addition, 3D scanning would make it feasible to compare a large number of landmark features when matching the scan of a bite-mark to the scan of a candidate dentition. This technology makes it possible to investigate the sources of error and quantify that error, and thereby has the potential to remove or at least reduce error including by limiting subjectivity associated with human judgement.

Study 3

To investigate the reliability and validity of measurements made with an intra-oral 3D scanner, two raters each measured 84 tooth and 26 arch features of 50 sets of upper and lower human dental casts first using digital hand-held callipers and second using the measuring tool provided with the ZFX IntraScan intra-oral 3D scanner applied to 3D images of the dental casts. The measurements were repeated at least one week later. Reliability and validity were quantified concurrently by calculation of intra-class correlation coefficients (ICC) and standard errors of measurement (SEM). The measurements of 110 landmark features of human dental casts made using the intra-oral 3D scanner were virtually indistinguishable from measurements of the same features made using conventional hand-held callipers. The difference of means as a percentage of the average of the measurements by each method ranged between 0.030% and 1.134%. The inter-method SEMs ranged between 0.037% and 0.535%, and the inter-method ICCs ranged between 0.904 and 0.999, for both the upper and the lower arches. The inter-rater SEMs were one-half, and the intra-method/rater SEMs were one-third, of the inter-method values. This study demonstrated that the ZFX Intrascan intra-oral 3D scanner with its virtual on-screen measuring tool is a reliable and valid method for measuring the key features of human dental casts.

Study 4

The aim of study 4 was to assess the accuracy of matching 3D images of 3D impressions of dental arches with 3D images of candidate dentitions. In this proof-of-concept study, dog dental arches were used as a model because demonstration of success in matching to dentitions with substantial variation due to inter-breed differences between dogs was a logical starting point. A further consideration was that there was greater access to dog dentitions than to human dentitions. 3D images of dog dental arches and their impressions were recorded using the intra-oral 3D scanner A single rater measured and re-measured 79 landmark dental features on each of the 3D images of 40 upper and the lower dog dental arches (positive images) using the virtual onscreen measuring tool provided with the intra-oral 3D scanner. This was repeated for 3D images of the impressions of dog dental arches in modelling clay (negative images). Measurements extracted from the images were used in an attempt to match the negative images to positive images. The measurements of 79 landmark features of the dog dental arches were nearly identical to measurements of the same features made on the impressions of dog dental arches on clay. The intra-rater intra-class correlation coefficients (ICCs) were greater than 0.937, and the intra-rater SEMs ranged between 0.041 and 0.076 for both the upper and the lower arches. Using the measurements of all 79 features, or even just those of anterior dentition, there was a 100% accuracy in matching the negative images to positive images of the dentitions. Nevertheless, some features contributed to the overall match rate more than the others. This study demonstrates that the portable intra-oral 3D scanner can record impressions of dental features with sufficient accuracy to allow identification of the dog-dentition that caused an undistorted bite-mark.

In conclusion, bite-mark evidence has the potential to provide supporting evidence to build a case against the human or animal perpetrator of a bite. Even when DNA evidence is available, and that is always not the case, supporting evidence from finger-prints and bite-marks helps to build a more compelling case. However, for bite-mark evidence to have probative value, it is necessary to address scientific criticisms of the methods used in obtaining it. In this thesis,this author proposes the use of intra-oral 3D scanning principally because of its potential for limiting and quantifying error. The reliability and validity of measurements of human dentitions has been established and a proof-of-concept of the accuracy of matching bite-marks with dentitions has been provided. A framework for future research is proposed, with recommendations for addressing the other limitations of bite-mark analysis. Specifically, the author proposes the establishment of databases of scanned images of dentitions of biting animals and map a path forward in the investigation of distortion in bite-marks.

Introduction

Background

Dental evidence in the form of bite-marks has been used in legal proceedings since 1692 (1, 2), and the number of bite-mark cases is on the rise internationally (3). The presence of bite-marks can be of considerable forensic importance (4) because forensic investigation of bite-marks may have the potential to provide evidence that is critical in identifying and prosecuting the perpetrator in cases of sexual assault, homicide, and child abuse (5).

Despite the long history of bite-mark evidence in courts, its evidential usefulness has been challenged recently (4). Although bite-mark analysis has the potential to be of great value to the judicial system (6), the scientific basis on which bite-mark analysis rests has not been established (2). As a result, bite-mark analysis has been subject to substantial criticism by judicial review groups (7).

Most recently, in the USA in September 2016, the the President's Council of Advisors on Science and Technology (PCAST) (8) reported on the steps required to strengthen forensic science and to ensure the validity of forensic evidence. The PCAST report stated that bite-mark evidence along with other pattern matching disciplines were introduced into criminal investigations with very little scientific validation, determination of error rates, assessment of reliability and the inability to outline their limitations as a discipline.

Also in the USA in 2016, the Texas Forensic Science Commission after a six-month investigation concluded that the scientific validity of bite-mark analysis is yet to be established and has made a recommendation to halt the use of bite-mark evidence in criminal trials until the scientific validity of bite-mark analysis has been established. The commission recommends the establishment of sound criteria for the use of bite-mark analysis, mainly to exclude a person of suspicion (9).

Prior to the PCAST report, in 2009 the National Academy of Science (NAS) reported the limitations of forensic techniques (10). The re-examination of cases resulting in wrongful convictions of individuals and their subsequent exonerations through DNA analysis prompted a review of forensic evidence by the National Academy of Science. In its report, the NAS was highly critical of the pattern matching disciplines, including bite-mark analysis. In its report, the NAS suggested that bite-mark analysis lacked scientific credibility and outlined the limitations of bite-mark analysis.

In Australia, the The Innocence Project Inc was founded as a pro-bono project at the Griffith University Faculty of Criminology and Law in Brisbane, Queensland. The aim of the The Innocence Project Inc is to act on behalf of individuals who were or are convicted wrongfully either due to lack of science or due to misconduct of science. The The Innocence Project Inc has found that evidence by experts in bite-mark analysis and several other forensic disciplines have resulted in several persons being wrongfully incarcerated (7). DNA analysis has been by the The Innocence Project Inc as a tool in exonerating individuals that were wrongfully incarcerated due to the use of the previously mentioned forensic disciplines. In the USA, there have now been 24 cases in which convictions of individuals based on bite-mark analysis have been overturned as a result of DNA evidence (12). This has led to calls for suspension of bite-mark evidence until its scientific credibility can be established (8), and even to recommendations to discontinue the use of bite-mark evidence in criminal investigations in the USA (9). The The Innocence Project Inc argues that apart from DNA, forensic disciplines including bite-mark analysis have not been subjected to rigorous scientific evaluation, which has resulted in a large number of wrongful convictions (11).

Although there have been suggestions to suspend the use of bite-marks as evidence until its scientific credibility can be established (9), or recommendations to discontinue its use altogether (11), bite-mark evidence still has the potential to provide supporting evidence required to build a case and to exclude suspected perpetrators. Even when DNA evidence is available, supporting evidence from bite-marks may provide a more compelling case. However, for bite-mark evidence to have probative value, it is necessary to address scientific criticisms of the methods used in bite-mark analysis.

The studies conducted in this thesis are aimed at reviewing and addressing the fundamental limitations of bite-mark analysis as a path forward in establishing the scientific credibility of bite-mark analysis. The content of this thesis is presented over seven chapters. In Chapter 1, a detailed review of forensic odontology, current techniques used in recording bite-marks and their limitations, and research relevant to this thesis are presented. Chapter 1 aims to provide the background, context and rationale for the research presented in this thesis. This chapter discusses in detail the role of forensic odontology, especially that of bite-mark analysis in the legal system, introduces the various stages involved in bite-mark analysis, discusses problems associated with some of the techniques currently used in bite-mark analysis, and briefly outlines previous research relevant to this thesis.

An important first step was to undertake an assessment of the public health implications of bites inflicted on humans by estimating the frequency of occurrence of the injuries and deaths caused. The author's investigations revealed that there is incomplete and fragmented information on bites perpetrated by humans on humans most commonly in cases of sexual assault and child abuse. Instead the author turned their attention to bites perpetrated by other biting animals, and specifically by dogs because dog-bites are the most common. In Chapter 2, the frequency of occurrence of bites, the annual age- and sex-specific incidence of injuries due to dog bites in Australia during 2001-2013 was investigated.

Forensic investigation of bite-marks has the potential to provide evidence that can be used to identify the perpetrator of a bite. Bite-mark evidence has been used in legal proceedings since 1692 but, recently, bite-mark analysis has been subject to substantial criticism. It was critical to address the limitations of bite-mark analysis identified in the NAS report, and to recommend a way forward. In Chapter 3, the fundamental limitations of bite-mark analysis are reviewed and the use of 3D imaging technology as an approach to overcome limitations of current methods of bite-mark analysis is proposed.

Prior to using 3D scanning tools in bite-mark analysis, the reliability and validity of measurements of landmark dental features, made with an intra-oral 3D scanner had to be investigated. Chapter 4 discusses the steps involved in assessing the reliability and validity of measurements of landmark dental features made with an intra-oral 3D scanner with a traditional handheld digital caliper as a comparison measure.

Once the reliability and validity of the intra-oral 3D scanner was investigated, the accuracy of matching 3D images of impressions of dog dentitionswith 3D images of candidate dentitions had to be investigated. Chapter 5 discusses the process of assessing the accuracy of matching 3D images of impressions of dog dental arches with 3D images of candidate dentitions. In Chapter 5, the ability of the Zfx IntraScan intra-oral 3D scanner to record impressions made by dentitions and the accuracy of matching 3D images of impressions of dog dental arches to 3D images of candidate dentitions are assessed.

Chapter 6 provides a summary of the studies conducted in this research, highlights the key findings of the research and their significance, and discusses the implications of the findings from this research.

Based on the findings presented in this thesis, some critical steps for future research on the establishment of databases of scanned images of dentitions of biting animals and the investigation of distortion in bite-marks are outlined in Chapter 7.

In conclusion, bite-mark evidence may be valuable when it is used as supporting evidence to build a case. Even when DNA evidence is available, supporting evidence from bite-marks may provide a more compelling case. However, for bite-mark evidence to have probative value, it is necessary to address scientific criticisms of the methods used in bite-mark analysis. To address the criticisms, it is critical to have a thorough understanding of the background of forensic odontology, and bite-mark analysis in particular. Chapter 1 presents a detailed review of forensic odontology, current techniques used in recording bite-marks and their limitations, and previous research relevant to this thesis.

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Chapter 1: Literature review

Preface

Chapter 1 aims to provide the background, context and rationale for the research presented in this thesis. Chapter 1 is divided into three sections. Section 1 highlights the role of forensic science, briefly discusses the various forensic science disciplines, and discusses in detail the role of forensic odontology, especially that of bite-mark analysis in the legal system. Section 2 introduces the methods currently used in recording patterned injuries including bite-marks, and discusses problems associated with some of the techniques currently used in bite-mark analysis. Section 3 briefly introduces 3D technology, discusses research related to bite-mark analysis using 3D technology and provides an overview of the Zfx IntraScan intra-oral 3D scanner.

Section 1: Role of forensic odontology

1.11 Introduction to forensic science

The Merriam-Webster Medical dictionary defines forensic science as the “application of scientific principles and techniques to matters of criminal justice, especially relating to the collection, examination, and analysis of physical evidence”[1]. Forensic science has also been defined as an interdisciplinary endeavour aimed at identifying valuable information by examining the remnants of an activity that may be used in identifying an activity or its source [2].Forensic science is a consortium of several forensic disciplines, and each of these forensic disciplines has an important role in forensic investigations [3]. Forensic disciplines such as crime scene investigations and cyber-crime investigations are conducted to assess the modality or style of a crime. Forensic pathology, forensic toxicology, forensic investigations into fire and explosions and structural failures, and vehicle accident reconstruction are applied to investigate how a crime may have occurred. Forensic odontology, DNA analysis and fingerprint analysis may be used in establishing identities of perpetrators responsible for crimes. They may also be used in linking a series of crimes perpetrated by a single individual or a group of individuals. Forensic anthropology is applied in identifying unknown victims of crimes or disasters. Forensic sciences such as micro analysis and examination of trace evidence, document examination, taphonomy, tool marks analysis, footwear analysis, tyre and impression analysis, fire-arms investigation and blood stain pattern analysis may be used in linking crimes to crime scenes. Forensic psychology and forensic psychiatry aid in understanding the motive behind the crimes by assessing the mental state of the perpetrators [4]. The process of collecting and examining forensic evidence through the application of various forensic disciplines is the principal component of forensic investigations [5]. Evaluation of combinations of evidence identified through the application of different forensic disciplines may be critical in reconstructing the crime scene to produce a better understanding of the crime and to establish the identities of perpetrators responsible for that crime.

Forensic evidence can be circumstantial evidence or corroborative evidence [6]. Circumstantial evidence supports the main fact in dispute [7]. As an example, the sighting of the suspected perpetrator in the area in which the crime occurred could be used as circumstantial evidence. On the other hand, corroborative evidence is any piece of evidence that boosts the probative value of another piece of evidence [6]. For example, the sighting of a suspected perpetrator in the area in which the crime occurred may be supported by the presence of their footprints in the vicinity of the crime scene or presence of DNA, fingerprints or dental evidence on a victim. The different types of forensic evidence are examined and reported by experts in particular forensic disciplines. Experts practicing forensic odontology are called forensic odontologists and are responsible for examining and reporting dental evidence [8].

1.12 Forensic odontology

The science of collecting, examining and reporting on dental evidence is termed forensic odontology or forensic dentistry [9]. Forensic odontology is primarily applicable in the following areas of medico-legal situations. Dental evidence is used for anthropological reasons in determining the approximate age and sex of unknown or unidentified individuals. Dental age estimation is also important in estimating ages of criminals who may claim to be underage to avoid heavier penalties [10], or of individuals seeking refuge in another country, individuals with no identification documents, children of unknown age who are up for adoption [11], and in cases of establishing ages of unaccompanied minors [12]. Along with determining dietary habits of individuals [13], examination of dental evidence may provide vital information about the occupation of an individual [14]. For example, carpenters may have a notch created on the incisal surface due to the habit of holding metal nails between the upper and the lower incisors. The oral cavity may provide information regarding the socio economic status of individuals [15], in identifying victims of mass disasters [16, 17] and in the diagnosis, examination and evaluation of oro-facial injuries [18]. Dental evidence in the form of bite-marks has the potential to provide vital information in identifying the perpetrator responsible for the crime [19, 20].

1.13 History of forensic odontology

1.13.1 International

Forensic odontology and its application in legal proceedings can be traced to the medieval period, where impressions of teeth on wax were used to seal important documents as a sign of their authenticity [21]. Records suggest that dental identification has been used for about two thousand years, and has been recorded in the History of Rome [21]. One of the first known significant uses of forensic odontology was in the late 19th century. On the 4th of May 1897 in Paris, France, 126 individuals perished in a fire at the Bazar de la Charite. The identities of 30 individuals could not be established visually, requiring identifications based on dental findings. While speaking on behalf of the other dentists involved in the identification process, Dr. Amoedo who is considered to be the father of modern forensic dentistry, described the findings upon completion of the identifications [19]. Reference to bite-marks and other dental identifications can also be seen in a treatise that was published on forensic medicine in 1920 by Dr. Wilfred Derome [19]. In 1949, a group of more than 40 dentists assisted in the identification of the victims when the S.S Noronic was destroyed by fire. A total of 108 victims was identified using dental records, making it one of the major historical disasters to have used dental identification on a large scale [19]. Although historically dental evidence has been used in establishing identities of individuals, dental evidence in the form of bite-marks has also been presented in courts of law. Of all types of dental evidence, bite-mark evidence has been the most controversial, and is the main focus of this thesis.

1.13.2 Forensic odontology in Australia

This section discusses the evolution of forensic odontology in Australia. Although limited, some historical applications of forensic odontology in Australia have been documented. The earliest recorded identifications using dental evidence were those of murder victims Bertha Couphlin in 1923 and Norman List in 1924 that have been referred to by Taylor in “A brief History of Forensic Odontology and disaster victim identification practices in Australia” [22]. In 1930, the crashing of a passenger aircraft into Botany Bay resulted in the death of ninety individuals. Although identities of victims were established using dental evidence, very little detail was recorded on the procedures involved. One of the major developments from this incident was the introduction of the Disaster Victim Identification (DVI) forms that could be used by the New South Wales Police, that are similar to those currently used by Interpol in DVI situations[22].

One of the most famous cases of dental identification in Australia occurred in New South Wales in 1934. In this case, the "Pyjama girl" remained unidentified for 10 years. The badly burnt remains of the victim were found to be covered only in pyjamas and hence the name. A local dentist Dr Jackson examined the victim several times, and in the process, extracted the victim's teeth three times over the ten-year period. Despite the repeated examinations and the multiple extractions, the dentist failed to correctly identify all restorations and even misidentified one tooth. Due to the lack of a record keeping routine, the victim's dentist compiled an ante-mortem chart chiefly based on his recollection of the services provided to the victim. This case highlighted the lack of good dental record keeping practices in Australia and the importance of having access to good dental records for medico-legal investigations. These discrepancies resulted in the victim remaining unidentified until 1944. In 1944, the case was reviewed by another dentist, Dr Magnus, who correctly identified the teeth and the restorations, and subsequently matched the dental findings to that of Linda Agostini. Linda Agostini's husband Antonio Agostini eventually admitted to having murdered Linda in 1934 [22]. In 1980, another case that garnered wide media attention was that of the disappearance of Azaria Chamberlain. The mother, Lindy Chamberlain was convicted of murdering baby Azaria. The conviction was overturned and the disappearance of baby Azaria has since been attributed to a dingo [23].

Forensic dentistry was not recognised as a specialised discipline in Australia at this time and dentists only occasionally assisted police investigations. The limited knowledge on forensic odontology resulted in a delay in correctly establishing the identity of the victim and a subsequent delay in convicting the perpetrator. The practice of forensic odontology as a discipline, began at different times in each Australian state and territory and prior to the 1950s, forensic odontology services in Australia were ad hoc. In Victoria and Western Australia there is very little record of utilization of forensic dentistry prior to the 1950s. In New South Wales, a formal position of a consultant forensic dentist in the State Public Health Department was established in the early 1960s. In South Australia, the first forensic odontology team to assist in Disaster Victim Identifications was not established until 1978 [21]. In Queensland, it was not until 1974 that a full-time position for a forensic odontologist was created. In Tasmania, prior to 1989, a senior dentist from Hobart handled all forensic odontology cases for several years. In Northern Territory, a part time oral surgeon in the government health service provided the early forensic odontology services. In the Australian Capital Territory, no forensic odontology services were provided until 1990. More recent bite-mark cases from Australia are discussed in detail later in this section.

1.14 Bite-marks as a branch of forensic odontology

Impressions or marks of human and non-human antagonist teeth [24] left on substrates or surfaces that can be marked by such means are called bite-marks [25, 26]. Simply put, bite-marks are patterns made by teeth biting something. When found on skin, dental evidence in the form of bite-marks can be important evidence in violent crimes [24, 27-29], child abuse cases [24, 30, 31], sexual assaults and homicide [20]. During criminal investigations, bite-marks are examined and compared with suspect dentitions as a means of attributing their source [31, 32]. Bite-marks may be found on both living and deceased individuals, may be found on bite-mark recipients [19, 26, 31, 33] and can either be human or non-human in origin [34].

1.15 History of bite-mark evidence in courts

Bite-mark evidence has been used in courts since the 1600s. This section discusses some landmark bite-mark cases, where dental evidence was used in convicting suspected perpetrators.

One of the earliest records of bite-mark evidence in a court of law dates back to 1692 in the American judicial system [26]. Several cases have been recorded in the US since then. These cases have been widely reported in the literature. In some cases, bite-mark evidence was found to be insufficient for conviction [26]. There have also been cases where the use of bite-mark evidence has led to wrongful convictions of individuals, for example Robert Lee Stinson 1984, Milone 1973, Willie Jackson 1989 and Ray Krone 1992 [35].

In Canada, the first known court case involving bite-mark evidence was on the 14th November, 1924. Bite-mark cases have also been documented in modern Europe, the United Kingdom, modern Africa, Vierfontein (free state), and India [36] resulting in convictions of the suspected perpetrators. Even in Australia, some cases with bite-mark evidence have been presented in courts.

1.16 Landmark Australian bite-mark cases

In Australia, bite-marks have been presented as evidence in courts. Some landmark cases are discussed below. Two well cited and highly critiqued bite-mark cases in Australia are the Raymond John Carroll case (1973) [37] and the Michael Lewis case (1985) [38, 39] where bite-marks observed on the victims were presented as expert evidence by forensic odontologists.

In 1973, in R vs Raymond John Carroll [37], a bite-mark was found on the thigh of child strangulation victim Deidre Kennedy. It was not until 1984 that the bruise mark was attributed to the suspect; Raymond Carroll was at that time being investigated by the RAAF for an unrelated offence. The court found him guilty based on the evidence provided by three expert forensic odontologists who had reviewed the dental evidence and compared it with the suspect's dental casts. Their expert reports concluded that each of the experts was able to successfully identify marks found on the child’s thighs as those belonging to the accused. Two of the experts presented evidence indicating that the marks found on the upper part of a photograph of the thigh were caused by the lower teeth, but the third expert was of the opinion that they were caused by the upper teeth. These varying opinions were due to the marks found on the victim being bruise marks and not bite-marks. Reservations around the varying opinions amongst the experts and the presence of bruise-marks instead of bite-marks resulted in the courts not accepting the expert evidence. However, rejection of bite-mark evidence did not impact the "Not Guilty" verdict pronounced by the Court of Criminal Appeal (CCA).

In 1985 in R vs Michael Lewis [39], Michael Anthony Lewis was suspected of sexually assaulting a young female as she made her way out of a disco heading towards the lodge where she was staying at the time. After the alleged assault, the accused summoned a taxi to take the victim to the hospital. Once at the hospital, the victim’s partner who in retaliation was bitten on the chest by the accused before he fled the scene attacked the accused. Forensic odontologists whose opinions were that there was a very high degree of certainty that the suspect was the source of the bite-marks examined dental evidence in the form of photographs and casts. The forensic odontologists supported their expert evidence by referencing the outcome of a single study of 360 cases of bite-marks in which the researcher concluded that each bite-mark could be individualized [39]. The court rejected this evidence and concluded that the "experts" that presented the evidence in this particular case had no first-hand experience in human bite-mark analysis, that the evidence was clearly based on works of other researchers and that it was important to be able to exclude the rest of the population as suspects rather than to simply establish similarities between a bite-mark and a suspect's teeth. The judge regarded the bite-mark evidence to be inadequate for judgment of conviction in this particular case and stated that "I do not consider it (bite-mark evidence) was of itself a sufficient foundation for conviction. There may be cases where it will be a link in a chain of circumstantial evidence, but here upon my view, there was no chain [38]."

Bite-mark evidence played an important role in both of the above cases, but was not accepted as expert evidence by the respective courts because it was considered to lack scientific validity. In R vs Raymond John Carroll, the probative value of the bite-mark evidence was questioned by the court, and in R vs Michael Lewis, the courts found the methods employed by the expert witnesses in analyzing bite-mark evidence to be scientifically deficient [37, 38]. The inability of forensic odontologists to demonstrate uniqueness of dentitions was also considered to be an important limitation.

In Australia, a third case has also been documented in the more recent past. In 2005, a young female was examined following allegations of sexual assault [40]. She presented with injuries that included a semicircular bruise in the mid-scapular position along with injuries to the face, arms and the back. The bruising was observed to be patterned and exhibited the class characteristics of a human bite-mark. These injuries were photographed and compared with the dental casts of the suspect. It was concluded that the injury was a bite-mark and that the source of the injury was an adult dentition. The forensic odontologist who inspected the bite-mark concluded that concurring features were observed between the patterned bite-mark injury and the suspect's dentition and that the bite-mark evidence could be presented as corroborative expert evidence if the case progressed to court. The complaint was withdrawn before it progressed to court [40]. Nevertheless, this case demonstrates that bite-mark evidence can be used in courts as supportive evidence if and when the quality of the evidence is high and when sufficient detail can be recorded from the bite-mark. Although there have been no convictions based on bite-mark evidence in Australia, bite-mark evidence is used in the Australian judicial system.

1.17 Conclusion

The purpose of bite-mark analysis is to examine and identify landmark dental features on bite-marks that can be compared and matched with those found on the suspect dentition. This information may be used in court to prove that the suspect was in violent contact with a victim at the time the crime was committed [41]. Forensic odontologists have the skills required to examine, record, identify and compare landmark dental features found on bite-marks to those found on the suspect's dentition [20, 41]. Although there have been successful convictions, flawed bite-mark analysis has also resulted in wrongful convictions. It may be important to understand the process of examining, recording and analysing bite-marks along with problems associated with this process. The aim of the next section is to discuss the methods involved in recording bite-mark evidence and to outline the problems associated with these methods.

Section 2: Current practices and methodologies of recording bite-marks

Preface

Bite-mark analysis involves examination of a patterned injury, confirming the injury as a bite-mark, examining dental characteristics and features found on bite-marks, and comparing them to those found on a suspect's dentition with the aim of excluding or not excluding the suspect as having made the bite-mark [42]. The purpose of this section is to review the processes and methods currently used in recording bite-marks and to discuss the problems associated with methods currently used in recording bite-marks and suspect dentitions.

1.21 Global authority in forensic odontology

The ABFO is the governing authority of forensic odontology in the United States of America and has become its global authority. To establish necessary standard practices and qualification for those interested in practicing forensic odontology, the American Board of Forensic Odontology (ABFO) was formed in 1976. Nevertheless, over the years, several societies representing forensic odontology have been established. The Australian Society for Forensic Odontology in Australia, the American Society of Forensic Odontology in the US, the British Association of Forensic Odontology in the UK, and the New Zealand Society for Forensic Odontology in NZ, Forensic Odontology Society of Philippines and the Indian Association of Forensic Odontology in India are some of the prominent establishments from around the world. The American Board of Forensic Odontology (ABFO) established professional guidelines for recording bite-marks and suspect dentitions. These guidelines are followed widely, including in Australia and are discussed below.

1.22 ABFO guidelines on recording bite-mark evidence

The American Board of Forensic Odontology outlined the first set of standard professional guidelines for the collection and analysis of bite-mark evidence, which are briefly described below. In its statement of purpose, the ABFO stated that, "Careful use of these guidelines in bite-mark analysis will enhance the quality of the investigation and the conclusion" [43].

Once patterns are confirmed as being bite-marks, they are recorded for further analysis. The American Board of Forensic Odontology has recommended that photographic documentation of the bite-mark must be made using digital and/or conventional imaging techniques. The ABFO recommends that these photographs should either be taken by the forensic odontologist, or under the odontologist's direction, in order to ensure that the procedure is accurate with complete documentation of the bite-mark. The ABFO states that it is important to take close-up photographs in high resolution using an ABFO No 2 scale (Figure 1). It must be ensured that the scale is placed on the same plane as that of the bite-mark and the camera. Photographs of the bite-mark with and without the ABFO No 2 scale must be taken with the three reference circles entirely visible. In addition to the ABFO No 2 scale, a linear scale and a circular reference should also be included.

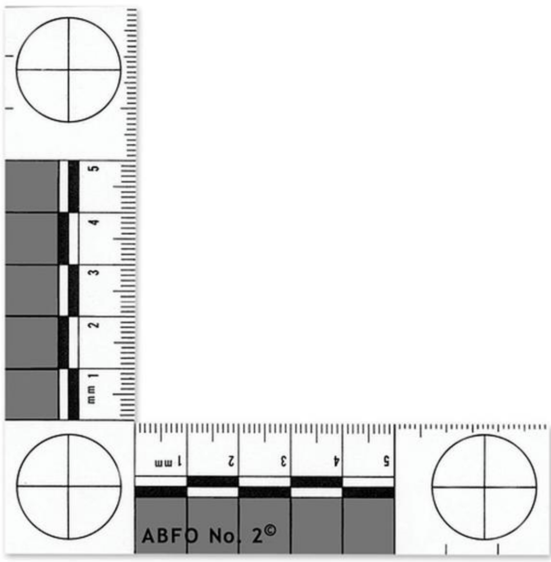

Figure 1.1 shows an ABFO No 2 scale commonly used in bite-mark analysis

Impression making techniques are used to record patterned injuries and suspect dentitions. The ABFO recommends that impressions of bite-marks must be made using Synthetic poly-ether based impression materials and silicone elastomers such as polyvinyl siloxane [44]. There is a wide range of impression materials that can be used in making impressions [45]. Depending upon the material of choice by the forensic odontologist, and following the recommendations of the manufacturer of that material, impressions of bite-marks are made. Once the material has set, the ABFO recommends removing the impression from the skin with great care. The ABFO recommends casting the impression material immediately using dental stone [44]. The current material of choice is polyvinyl siloxane [26].

Both methods used in recording bite-marks and suspect dentitions may be associated with drawbacks that may affect the outcome of the bite-mark analysis as a consequence. These disadvantages may contribute to unreliable information of dental features obtained from the bite-marks. Drawbacks associated with methods currently used in recording bite-marks are discussed below.

1.23 Use of photographs to record bite-marks

As described earlier in this section, the first method of recording bite-marks is through the use of photographic methods. The use of photographs in recording and preserving dental evidence has been considered to be critical in bite-mark analysis [46]. Digital imaging of bite-marks has evolved as one of the commonly used methods in bite-mark analysis [47]; however, photographic techniques used in recording bite-marks have some limitations. These are discussed below.

1.23.1 Problems with using photographs to record bite-marks

There are two problems associated with photographing bite-marks. Firstly, it is a 2-dimensional interpretation of 3-dimensional information [48]. A second important factor that affects the appearance of bite-marks is distortion. Distortions occurring due to factors associated with photographic techniques are termed photographic distortions. Even when using imaging techniques that are recommended by the ABFO, photographs of bite-marks may not always be accurate and may be distorted. The ABFO guidelines recommend the use of a camera flash , when appropriate, while photographing bite-marks [49]. However, when external flash units for photographing bite-marks are used incorrectly, bright areas or hot spots may appear on the photograph. Also, the external flash unit may inadvertently be mounted on a different plane than that of the camera lens. This may result in darkening of the bottom of the image. This problem can be solved by using a diffuser to distribute light uniformly across the field of view; however, this would require a large amount of equipment that needs to be taken into the field each time [50]. Some distortions may also occur due to the lens used in photographing images. Errors may occur due to perspective when camera lens are placed too close to the surface being photographed. This may cause enlargement of the object closest to the lens surface causing ballooning of the surface being photographed. This may be avoided by using telephoto lens with focal lengths between 100mm and 150mm and by ensuring that there is sufficient distance between the lens and the subject being photographed [51].

Photographic distortions occurring due to incorrect photographic techniques may result in sub-standard evidence [52]. Photographic distortions can further be classified into four different types. They are discussed in the following section.

1.23.2 Types of photographic distortion

The American Board of Forensic Odontology guidelines recommend that an ABFO No 2 scale be used such that the bite-mark can be scaled. However, it has been mentioned in the existing literature [52, 53] that including a scale while photographing bite-marks can also result in distortions, because it may not be possible to place the scale accurately along the plane of the injury. Bite-marks on skin usually occur on curved surfaces and placing a flat scale may result in distorted images. The degree to which this graphic representation is accurate depends on many variables, including the orientation of the scale and the camera with respect to the bite-mark injury [52]. The resultant photographic distortions can thus be further sub-divided into the following categories:

i) Type I distortion

Type I distortion occurs when either or both the bite-mark and the scale are not parallel with the plane on the camera [52, 53]. These distortions may give rise to errors that cannot be corrected [51].

ii) Type II distortion

Type II distortion occurs when the scale is not perpendicular to the lens of the camera [52, 53]. Such distortions can be corrected but Forrest et al recommend against attempting any corrections on such types of distortions [51], because there is potential to introduce further distortions.

iii) Type III distortion

Type III distortion occurs when one of the two arms of the scale is distorted [52, 53]. Such distortions may be corrected by using the non-distorted arm as control and resizing the distorted arm accordingly.

iv) Type IV distortion

Type IV distortions may occur when the scale itself is bent or skewed [52, 53]. Such distortions cannot be corrected. The four different types of photographic distortions are depicted in Figure 2.

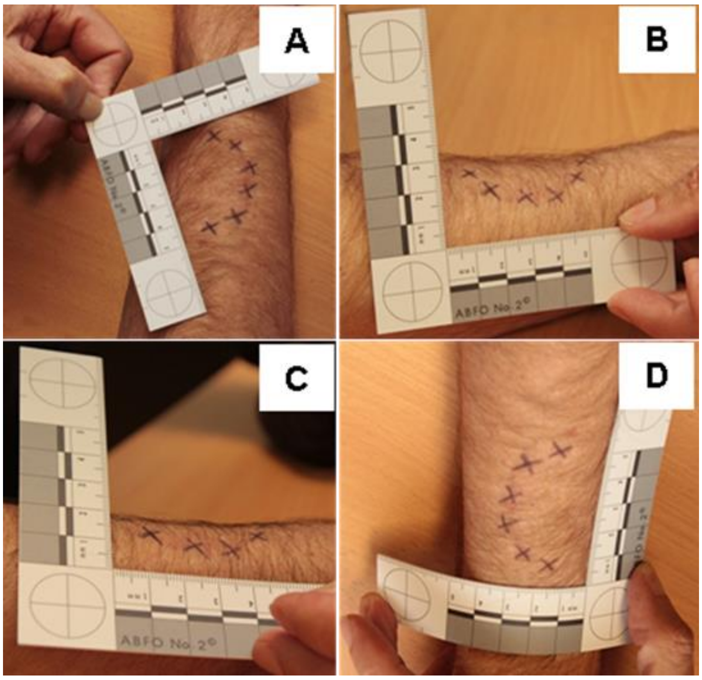

Figure 2 depicts the four different types of photographic distortions.

Photographic distortions may occur due to a single factor or a combination of factors. These factors include: a) wrongful arrangement of the scale, b) use of improper lighting, and c) the time required to determine the correct aperture that can be used to photograph bite-marks. Photographic distortions due to incorrect placement of scales or incorrect positioning of the camera may be corrected to an extent; however, this may result in further avoidable distortions [51]. Photographic evidence can be deemed invalid as a result of distortions, deeming the evidence un-reliable [52]. Even though photographs of bite-marks are 2-dimensional interpretations of 3-dimensional information, Martin-de-las-Heras and Tafur [48] have recommended that photographs of bite-marks must still be made for record keeping purposes.

1.24 Use of impression making techniques to record bite-marks

Taking impressions of bite-marks and comparing them with dental casts have been standard practice in forensic investigations of bite-marks [33, 44, 54-58]. However, these long-standing practices of impression making and dental casting may have some drawbacks that could result in inaccuracies in the resultant dental casts. It is important to understand each of these stages in detail to understand their drawbacks.

1.24.1 Problems with using conventional impression making and casting methods used in recording bite-marks and suspect dentitions

Dental casting is a two-staged process. Firstly, impressions of teeth and the surrounding structures are made using dental impression materials. Secondly, dental casts are made from these dental impressions using dental casting materials [59]. Dental impressions are the negative replications of teeth and their surrounding structures [60]. Dental impression techniques have been used due to their cost effectiveness and the availability of a wide range of impression materials that can be used for various procedures that require casting [45]. However, some disadvantages associated with these impressions have been identified. Impressions are found to have deficient dimensional stability [61]; the procedure is time consuming [62]; impression materials are associated with expansion [63]; impressions are prone to shrinkage and distortion [63]; impressions are susceptible to loss of detail due to physical damage [64]; and impressions are subject to inherent errors associated with impression making techniques [45]. Synthetic polyether-based materials, such as silicon, that have been used to make impressions of bite-marks [44] may undergo structural and chemical changes while setting. This may cause drying of the underlying skin or introduce moisture into the skin, thereby altering the appearance of the bite-mark on the impression material [65]. Experts in the field consider that an ideal impression material without disadvantages does not exist [66, 67].

Dental casts are the positive replications of teeth and their surrounding structures that have been used in studying teeth and surrounding structures for research and diagnostic purposes [68]. Preparation of dental casts is time-consuming and the procedure causes discomfort to the subjects. Dental casts can take up large amounts of storage space [69, 70] and sharing them for research or consultation purposes is an inconvenience [71, 72]. Coupled with the above mentioned problems, the materials used in making dental casts may also undergo structural and chemical changes during the various stages of the casting procedure [73], potentially leading to dimensional inconsistencies between plaster teeth and the real teeth [59]. Such dimensional inconsistencies may result in inaccuracies when measurements of landmark dental features are made on them.

Although the ABFO guidelines do not make it mandatory for impressions of bite-marks to be made, the ABFO recommends taking impressions of bite-marks if and when possible for any additional information that it may provide.

1.25 Conclusion

Recording bite-marks is a complex process. Although the ABFO guidelines for recording bite-marks are widely used, there is little evidence to suggest their effectiveness in comparing and analysing bite-marks with suspect dentitions. In addition, distortions associated with recording bite-marks remain an issue. Recording dentitions using conventional methods is widely accepted, but it still has limitations. One way to improve the accuracy of bite-mark analysis may be to use a 3D record in comparison to 2D photographic methods as currently practiced. Even though the methods currently used to record bite-mark evidence have sometimes led to successful convictions (eg Theodore Bundy [74]), bite-mark analysis has been subject to recent criticism with critics arguing that it lacks the scientific credibility required for it to be admitted as evidence in courts. This thesis proposes the use of 3D scanners as a method of recording bite-mark evidence. The following section briefly discusses 3D technology and its applicability in forensic odontology.

Section 3 : 3D technology

Preface

The purpose of this section is to introduce 3D technology, to briefly outline its history and application in forensic odontology, and to discuss previous research conducted using 3D technology in forensic odontology, especially in bite-mark analysis. This section provides the background for the technology upon which the research that has been conducted in this thesis is based.

1.31 Introduction to 3D technology

3D imaging aids in creating images of objects in 3-dimensions [75]. 3D imaging tools currently available in the market are capable of providing 3-dimensional surface data in high-resolution. A 3D scanner creates geometric samples of a point cloud on the surface of the object being scanned. This information allows extrapolation of the shape of the object being scanned. Images created by 3D scanners can be used to describe distances between different points in the image[76].

1.32 History of 3D imaging

3D technology has existed for the past several decades. 3D scanning technology was first introduced in the 1960s, as an attempt to accurately record and recreate various objects [76]. Initially, the scanners comprised of cameras, projectors and lights as standard setup. This method was considered to be time-consuming. In 1985, white light, lasers and shadows replaced cameras and projectors in capturing surface information. By the mid-nineties, scanning technology had advanced, and full body scanners were developed. The advancement of 3D technology, and the introduction of 3D imaging tools has generated considerable amount of interest in the recent years [76]. This can be attributed to their applicability in a wide range of disciplines.

1.33 Applications of 3D imaging technology

3D imaging technology has several applications in industries such as in the fields of entertainment, robotics, manufacturing [77], in documenting historical art work [78], in the gaming industry [79], the apparel industry [80], and in medicine [81-83]. In the medical industry, 3D imaging has been widely applied in designing prostheses and bio-fabrication of organs [84], in dermatology, in imaging cardiac structures [85] in other medical imaging [86], in anthropology [87, 88] and in dentistry for therapeutic imaging [62, 89] and for orthodontic purposes [71, 72, 90]. The following section briefly outlines advantages of 3D technology in dentistry.

1.34 Advantages of using 3D imaging in dentistry

In clinical dentistry, 3D scanning is slowly replacing traditional casting methods due to the ability to archive study casts without the fear of damage or loss to the original casts. 3D scanning also reduces the amount of space required to store a large number of study models. It also facilitates treatment planning, thereby reducing the need for multiple visits by the patient. 3D images can also be used to simulate several treatment modalities such as closure of space after tooth extraction or expected pathway of tooth eruption, which can also be used to demonstrate to the patients the outcome of a particular treatment [91].

1.35 Application of 3D imaging in forensic sciences

3D scanning has been used in documenting evidence in criminal investigations [76, 92] in craniometry [93], in visualization and comparison of impressions on fired bullets [94], in facial recognition [95] and also in the analysis of injuries and injury causing instruments [96].

Along with other forensic disciplines, 3D scanning has been applied in forensic odontology for reconstructing skulls and jaws of victims of disasters [97], in researching and understanding dental anthropology [98], in the field of biometrics [99, 100], in imaging dento-alveolar trauma [101] and also in the analysis of bite-mark [54, 102-105].

Novel 3D impression making has been proposed as an alternative to conventional impression making techniques in forensic odontology [105]. Several studies have assessed the accuracy of the digital impression making techniques as an alternative to conventional methods of making impressions for therapeutic purposes [61, 63, 70-72, 106-112], but none for forensic odontology. This thesis investigates the use of 3D technology in bite-mark analysis and therefore some key studies that were conducted on using 3D imaging techniques in forensic investigations of bite-marks are discussed.

In 2003, Thali et al [54] discussed the use of 3D/Cad supported photogrammetry. In this study, the authors used a Picza surface 3D scanner to digitize dental casts of several individuals suspected to be the perpetrator responsible for a bite-mark on a homicide victim. In this study, the authors demonstrated the process of overlaying the 3D model of a suspect's dentition on a 2D image of the bite-mark. This study, according to the authors was the first 3D approach on a real bite-mark case. The limitation of the 3D scanner used in this study was that it was a table top scanner with limited portability and one that was not equipped to make 3D images of intra-oral structures.

In 2006, Blackwell et al [113] discussed the methodology for imaging human dentitions and their corresponding impressions in 3D. The authors used the FARO Gold Arm (a measurement instrument designed for use in engineering and manufacturing for controlling dimensional accuracy) and the ModelMaker H40 (a reverse engineering and inspection sensor attached to the end of the FARO Gold Arm) to create 3D images of 42 dental casts. The authors demonstrated the ability of the tool to create 3D images that could be used to match them with their corresponding 3D images. The limitations of the study were that the FARO Gold Arm and the ModelMaker H40 are bulky equipment, making it impractical for use on the field. Also, the procedure of scanning the impressions of dentitions that were made using type 3 low viscosity Hydroflex hydrophilic vinyl polysiloxane impression material required some pre-scan preparation procedures. To facilitate easy scanning, the impressions were sprayed with a fine powder as a method of reducing the shine on the surface of the impression.

In 2011, Bush et al [114] compared one hundred randomly selected mandibular 3D images from a sample of five hundred 3D images obtained from a dental laboratory. The aims of this study were to determine the importance of the third dimension in determining match rates for human dentitions and to compare measurements of landmark features obtained from 3D images with those of 2D images that were created by discarding the z-axis information from the 3D images. The authors concluded that measurements made on 3D images preserve additional information about the dentition. The limitation of this study was that the numbers of landmark features examined on 2D images differed from those of the 3D images because the 3rd dimension or the values for the z-axis was not used in the comparison process.

In 2011, Evans et al [115] described a novel 3D image capture method that could be used to capture bite-marks from human skin in 3 dimensions. The authors reviewed the use of the Mavis Stereo-photogrammetric camera system capable of producing 3D models of dental casts. The authors compared the precision and accuracy of a conventional 2D imaging technique and a novel 3D imaging system that uses a combination of a MAVIS camera and a Vivid 910 laser scanner in capturing images of dentitions. The authors of this study acknowledge that the best information from bite-marks could be obtained by 3D imaging tools such as the system described in their study. The authors conclude by indicating that although there are advantages in using 3D imaging tools in comparison to 2D imaging, the method demonstrated in this study lacked the ability to produce 3D images of high resolution. The limitations of this study are that the 3D image capture system described in this study is dependent upon a combination of two different systems, and is only capable of producing low resolution 3D images.

In 2012, Komar et al [116] explored the use of handheld 3D scanners to document crime scene evidence, including bite-marks. In this study, the authors discuss the potential scenarios that may require the use of 3D scanning. The scenarios suggested by the authors include scanning features of grave walls to record tool marks, in recording footprints, fingerprints on soft surfaces that are capable of recording them, tire marks and also in recording bite-marks. The authors used a Polhemus FastSCAN Scorpion 3-D laser scanner for 3D imaging. The limitation of this scanner is that it was a table top scanner capable of recording objects that could be rested on a table. The scanner was not equipped to scan images of teeth that were in situ.

In 2014, Stella Martin-De-Las-Heras et al [117] described a method of using the DentalPrint software © in comparing 3D overlays from dental casts with experimental bite-marks using geometric morphometric analysis. 3D images of dentitions and impressions of dentitions used in this study were made using a Picza 3D scanner and the comparison overlays were made using the DentalPrint software ©. In this study, the authors compared 3D overlays of dental casts with impressions of dentitions. The limitation of this study was that the 3D scanner used in this study to produce 3D images was a table top scanner capable of scanning things that can be mounted beneath the scanning surface, and therefore may not be suitable for use in imaging dentitions that are intact.

In 2014, An Molina and Stella Martin-De-Las-Heras [118] compared the accuracy of two different types of 3D scanners namely contact type and laser type 3D scanners. The authors scanned ten dental casts using both the scanners and measured seven linear measurements from each of the 3D images. The authors in this study demonstrated that although the two different types of scanners functioned differently, there were no statistically significant differences in the uncertainty values between the two scanners. The authors used a contact type PIX-3 model Picza 3D scanner and a 2020i Desktop 3D scanner for this study. The limitations of these scanners are that the PIX-3 model Picza 3D scanner is a contact type scanner, which may not be suitable for imaging in forensic casework because there could be potential damage to the surface being scanned due to the contact. Also, the 2020i Desktop 3D scanner for this study is a desktop scanner and therefore may not be a practical choice of 3D scanner that may be used in scanning teeth inside the oral cavity.

In 2015, Agnieszka et al [119] compared 2D and 3D analytical methods to investigate the possibility of identifying a biting dentition. The authors used an optical scanner GOM Atos II Rev. 01for producing 3D images of impressions of dentitions made on 4 different types of materials by 10 individuals. In this study, the authors concluded that 3D analytical methods were superior to the 2D method employed in this study, and that by using the 3D method, it was possible to identify the biting dentition in most cases. The scanner used in this study is a fixed scanner, with limited portability making it impractical for use on the field. Also, the scanner would not be practical for making intra-oral 3D images.

In 2017, Ramos et al [120], developed a new software "BitePrint" that was capable of semi-automatically recognising dental marks from photographs of bite-marks. The aim of this study was to calculate the same parameters of the biting edges as those from 3D images of dental casts and assess the ability of the software in comparing tooth marks recorded on skin to the biting edges of the suspect dental cast. Although the authors of this study did not assess the ability of 3D imaging tools in this study, they proposed a method of semi-automatically measuring dental land-marks from 2D and 3D imaging techniques. The authors conclude by indicating that it would be ideal to use 3D imaging techniques to record skin indentations for bite-mark analysis because they have minimal angular distortion, resulting in less measurement errors.

Recent advances in 3D imaging include intra-oral 3D scanners such as the Zfx IntraScan intra-oral 3D scanner that are capable of overcoming some of the limitations of the previously used

3D scanners. The following section briefly introduces the advanced, portable, Zfx IntraScan intra-oral 3D scanner and outlines some if its key features.

1.36 Zfx IntraScan Intra-oral 3D scanner and its features

The Zfx Intrascan intra-oral 3D scanner is lightweight and compact, making it ideal for use in fieldwork. The Zfx IntraScan intra-oral 3D scanner weighs 600g and is directly connected to a laptop computer through a single cable. The Zfx IntraScan intra-oral 3D scanner is a non-contact surface scanner that can record digital impressions of objects in 3-dimensions without making physical contact with the object, and therefore is non-invasive in its application. This suggests that dentitions and bite-marks made by teeth on skin can be scanned without making physical contact with the skin. Unlike previously used scanners, the Zfx IntraScan intra-oral 3D scanner is portable and does not use additional materials to enhance the features of the scan. Unlike previously used scanners, the Zfx IntraScan intra-oral 3D scanner permits the operator to pause and continue the scan in case of any interruptions. The built-in real-time stitching software allows the scans to be stitched into one complete image in the computer. Scanning is conducted by positioning the Zfx IntraScan intra-oral 3D scanner over the occlusal surface making sure there is no contact between the instrument and the teeth. Once that is ensured, the scanner is moved in a swivelling motion moving the scanning tip occlusally-palatally and back. Multiple scans of the same area can be made to ensure an improved accuracy of under 100mμ. The resultant image is transferred into the computer that is connected to the scanner as the scanning progresses. The final images are directly stored in STL format, hence reducing any post processing work time [121]. The images can then be examined using the measuring software provided along with the scanner.

1.37 Conclusion

As previously discussed, some research has been carried out using 3D technology, but the 3D imaging tools used are either bulky, use contact scanners for scanning objects or may not be used in the field due to portability issues. The Zfx IntraScan is an intra-oral 3D scanner that has been designed for use in clinical dentistry for making digital impressions of teeth and in enabling high quality restorations, but the scanner has not been assessed for its use in forensic investigations of bite-marks. The intra-oral 3D scanner has clear potential for application in forensic investigation, lacking only validation for forensic purposes because it overcomes the limitations of previously used 3D scanners.

The aims of this thesis were to investigate the frequency of occurrence of dog-bites in Australia because dogs are also capable of leaving bite-marks on their victims and also because it is a largely unrecognised public health problem, to propose the use of 3D imaging technology as an approach to overcome limitations of current methods used in recording dentitions and impressions of teeth for bite-mark analysis, to investigate the reliability and validity of measurements of landmark dental features on 3D images of dentitions made using the Zfx IntraScan intra-oral 3D scanner, and to investigate the accuracy of matching 3D images of dentitions to 3D images of their corresponding impressions made on clay and propose the 3D scanner as a potential tool that could be used in imaging dentitions and bite-marks. These studies are presented in the following four chapters.

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Chapter 2: The incidence of public sector hospitalisations due to dog-bites in Australia 2001-2013

Preface

An important first step in this research was to undertake an assessment of the public health implications of bites inflicted on humans by estimating the frequency of occurrence of the injuries and deaths caused. The author's investigations revealed that there was no information available on bites perpetrated by humans on humans most commonly in cases of sexual assault and child abuse, using which age and sex specific incidence could be estimated. Instead, the author turned their attention to bites perpetrated by other biting animals, and specifically by dogs because dog-bites are the most common. Chapter 2 discusses the frequency of occurrence of bites and the annual age- and sex-specific incidence of injuries due to dog bites in Australia during 2001-2013.

2.1 Introduction

Dog-bites have long been identified as a potential source of serious injury to humans (1), and injuries due to dog-bites are a largely unrecognized and growing public health problem. The public health implications of dog-bites are substantial, and verifying the extent of the problem is important (2). The serious health-related consequences of injuries sustained due to dog-bites include open wounds, cellulitis, infections and fractures leading to temporary or permanent disability, mental trauma and anxiety. The economic consequences include use of medical resources, lost productivity of victims and their carers, and time and effort expended by each of the wide range of personnel involved in apprehending and dealing with the offending animal including court cases involving the victim, the victim's family and the owner of the offending dog. The social consequences include inter-personal disputes and community conflict.

There is limited, incomplete and fragmented information on dog-bites in Australia due to the lack of a comprehensive reporting system (3, 4). The National Coronial Information System (5) produced a fact sheet on animal-related deaths of humans in Australia between July 2000 and November 2010. It highlighted that, on average, 1-2 persons died due to dog-bites each year. The Australian Companion Animal Council Inc. has estimated that more than 100,000 persons in Australia are attacked by dogs each year, with an estimated 12,000-14,000 individuals requiring treatment for dog-bite injuries, and around 10% of those being hospitalized each year (3). This may be an underestimate of the actual rates of hospitalization because, in the only national compilation of data (6) that was published in 2005, an average of 2184 persons each year were found to require hospitalization during 2001-03. The authors of the national report used the ICD-10-AM W54 code to estimate the incidence of injuries due to dog-bites. That code included other injuries from falls due to being knocked over by dogs. In 2002-03, ICD-10-AM w54 was sub-classified into ICD-10-AM W54.0 to record dog-bite injuries, and ICD-10-AM W54.8 to record injuries due to being struck by dogs respectively. To date, this has not been succeeded by another national report that has reported the incidence of hospitalizations due to injuries from dog-bites using the revised ICD-10AM W54.0 code.

A position paper published by the Royal Australasian College of Surgeons in 2012 (7) on dog-bites in Australia recommended updating the current data and investing in further research on the epidemiology of dog-related injury including dog-bites. To address this paucity of recent data, the aims of this study were to investigate the incidence, and trends in incidence, of hospitalization due to dog-bites in Australia during the period 2001-2013.

2.2 Method

2.2.1 Data Sources

Summary data on hospitalisations due to dog-bite-related injuries with an ICD-10-AM (WHO International Statistical Classification of Diseases and Related Health Problems, Tenth Revision, Australian Modification) code w54.0 (external cause of injury code) for public hospitals in each state or territory of Australia during the study period 2001-2013 were sourced from the Australian Institute of Health and Welfare for the period 2001-13. The AIHW summary data were provided in biennial (July 2001- June 2003, July 2003-June 2005,….,July 2011-June 2013) and sex-specific totals for age-groups 0-4, 5-9, 10-14, 15-24, 25-34, 35-44, 45-54, 55-64, 65-74 and 75+ years for states and territories. Data for Tasmania, ACT and Northern Territory were combined due to small cell counts in some age and sex categories.

Additional data from injury surveillance units and health department registries of each state and territory of Australia were used for state-based analyses. Mid-year estimates of the population of Australia in 5-year age-groups and sex-specific categories were sourced from the Australian Bureau of Statistics online resources (8). The study was approved by the Tasmanian Health and Medical Human Research Ethics Committee (HREC no H0013594).

2.2.2. Data analysis

The population estimates were aggregated to match the year, age and jurisdictional groupings in which AIHW hospitalization data were provided for each sex. Estimates of incidence density were calculated by dividing the number of hospitalisations due to dog-bite related injuries of persons of each sex in each year/age/jurisdictional grouping by the sex-specific population estimate for that grouping. Ninety-five percent confidence intervals for the incidence density were based on a normal approximation with the standard error of the logarithm of the incidence density estimated as the square root of the inverse of the number of cases. Trends in sex-specific incidence density were estimated by Poisson regression of the mean number of hospitalisations in each age/jurisdictional grouping of the mid-point of each year grouping and binary (0/1) terms for each age and jurisdictional grouping other than the reference category, and with the logarithm of the sex-specific population of the age/jurisdictional grouping entered as an offset. Quadratic terms in the mid-point of each year groupings were included to capture non-linearities.

2.3 Results

During the 12-year study period, a total of 31,218 persons (17,049 males and 14,169 females) were hospitalized for treatment for dog-bite injuries, at an average annual rate of 2601 per year and 12.39 (95% CI 12.25, 12.53) per 100,000 person years.

2.3.1 Age-and sex-specific incidence density

The highest rates of hospitalisations due to injuries from dog-bites were 25.95 (95% CI 25.17, 26.73) recorded for 0-4 year olds, followed by 18.41 (95% CI 17.75, 19.07) for 5-9 year olds. The lowest rates were 7.99 (95% CI 7.69, 8.29) per 100,000 for 15-24 year olds. Rates for persons aged 45+ years were generally stable at 12.11 (95% CI 11.89, 12.33) per 100,000. Table 2.1 presents age-and sex-specific estimates of incidence density for the study period 2001-13**.** In each category of age prior to 45-54 years, the number of cases among males exceeded the number among females, and male rates for hospitalisations due to injuries from dog-bites were higher than female rates. This male:female disparity was not continued at older ages, commencing with the 45-54 year age group.

Table 1.1: Age group and sex-specific rates of hospitalisations for dog-bite injuries

Age group	Males		Females	
	Cases	ID (95% CI)	Cases	ID (95% CI)
00-04 years	2356	28.13 (26.99, 29.26)	1879	23.65 (22.58, 4.72)
05-09 years	1617	19.44 (18.50, 20.39)	1368	17.33 (16.41, 18.25)
10-14 years	1022	12.03 (11.29, 12.76)	607	7.53 (6.93, 8.12)
15-24 years	1608	9.04 (8.60, 9.48)	1170	6.89 (6.49, 7.28)
25-34 years	2534	14.07 (13.53 ,14.62)	1489	8.32 (7.90, 8.74)
35-44 years	2319	12.69 (12.18, 13.22)	1705	9.21 (8.77, 9.64)
45-54 years	2128	12.44 (11.91, 12.97)	2115	12.18 (11.67, 12.71)
55-64 years	1627	11.87 (11.29, 12.44)	1694	12.35 (11.77, 12.94)
65-74 years	1004	11.43 (10.73, 12.14)	1030	11.27 (10.58, 11.96)
75+ years	834	13.12 (12.23, 14.01)	1112	12.17 (11.45, 12.88)
All ages	17049	13.61 (13.41, 13.82)	14169	11.19 (11.00, 11.37)

*ID (95% CI) = Incidence density (95% CI)

Figure 2.1 depicts the incidence and incidence density for each age group for both sexes combined, and the incidence rates for the study period. Rates were generally similar among adults commencing with 25-34 year olds, but the number of cases peaked for 25-34, 35-44 and 45-54 year olds and were similar to the number of cases among 0-4 year olds (5-year age span).

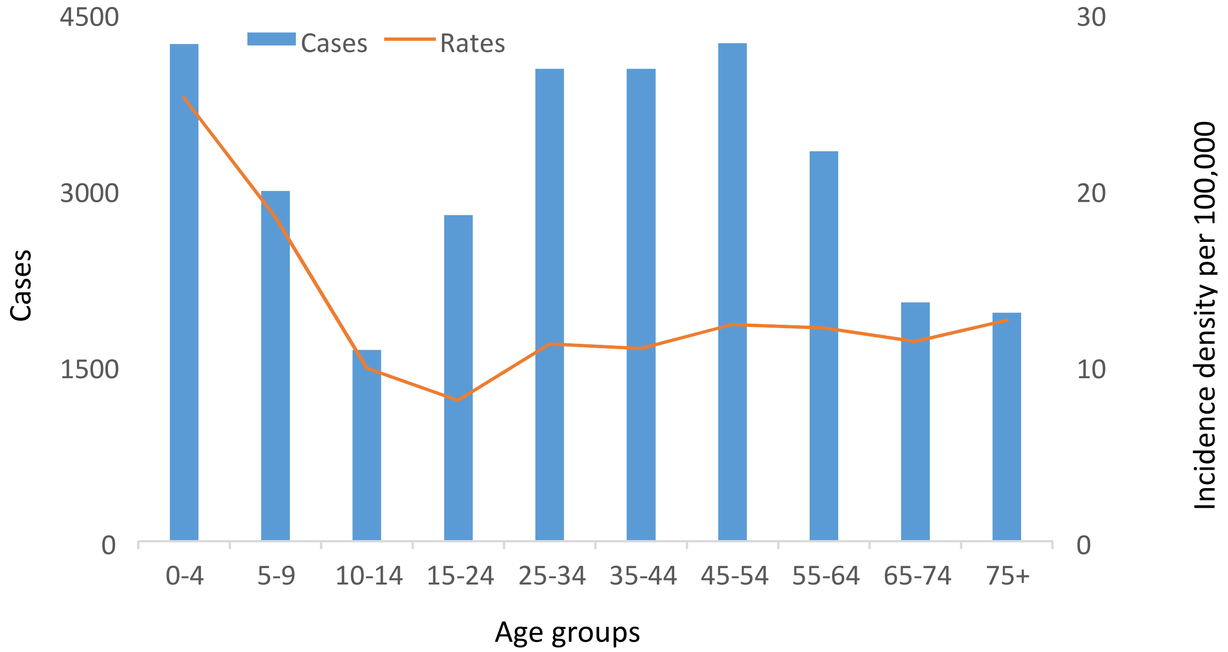


Figure 2.1: Age specific incidence and incidence density of hospitalisations due to injuries from dog-bites in Australia, 2001-13.

2.3.2 Biennial incidence and incidence density

Table 2.2 presents biennial estimates of incidence and incidence density of hospitalization due to injuries from dog-bites in Australia during the study period. The biennial rates for 2001-03 were 11.50 (95% CI 11.16, 11.84) per 100,000 males and females combined. Rates increased from 10.28 (95% CI 9.96, 10.59) per 100,000 during 2003-05, the low point of the period, to 13.63 (95% CI 13.29, 13.98) per 100,000 during 2011-13 for both sexes combined.

Table 2.2: Biennial incidence density of hospitalisations due to injuries from dog-bites in Australia, 2001-13.

Years*	Cases	ID (95% CI)
2001-03	4485	11.50 (11.17, 11.84)
2003-05	4100	10.28 (9.96, 10.59)
2005-07	4393	10.72 (10.41, 11.04)
2007-09	4892	11.51 (11.18, 11.83)
2009-11	6006	13.64 (13.29, 13.98)
2011-13	7342	16.15 (15.78, 16.52)

*(From 1st July of the first year to 30th June of the second year in each year grouping)

Figure 2.2 depicts the biennial incidence density during the study period. Rates rose progressively after 2001-03, with a more substantial increase in incidence rates after 2009. The increase in rates after 2001-03 is closely approximated by a quadratic trend on the logarithmic scale.

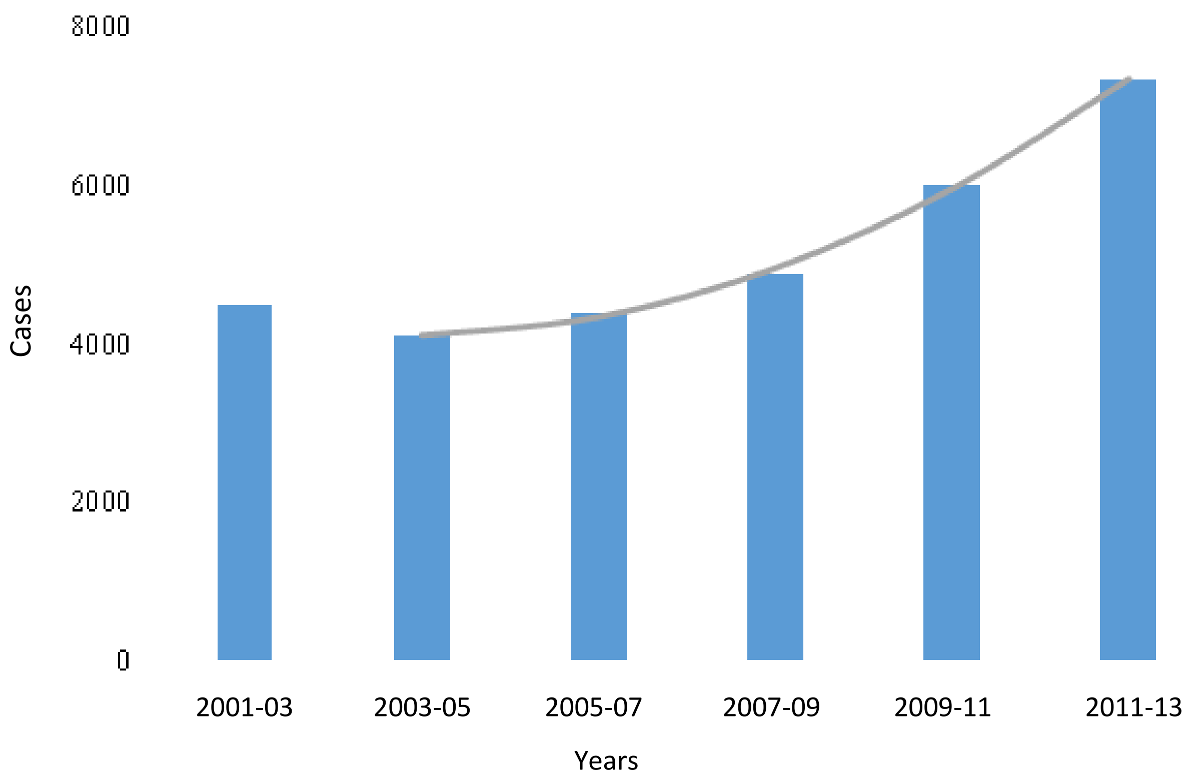


Figure 2.2: Biennial incidence density of hospitalization due to injuries from dog-bites in Australia 2001-13

2.3.3 State and territory incidence density

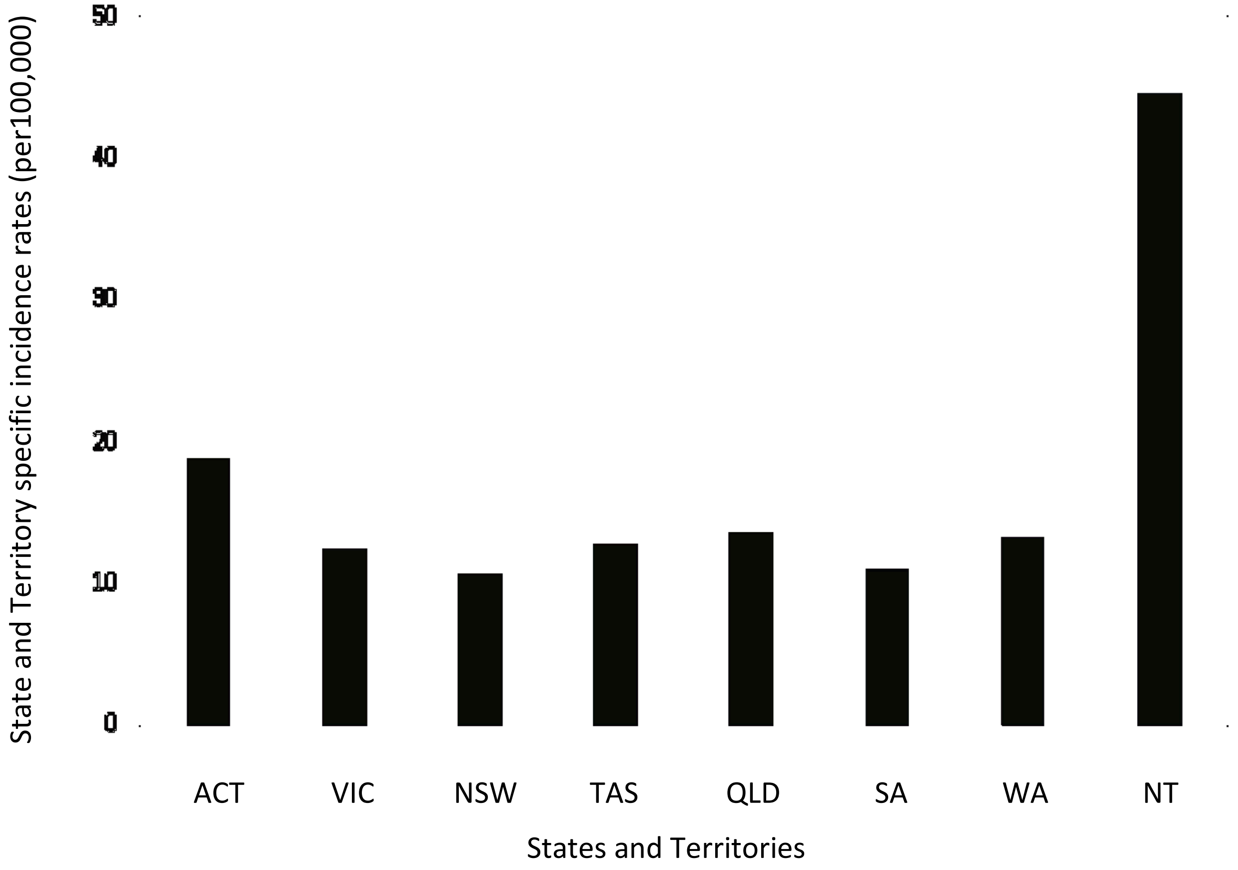
Table 2.3 presents state and territory-specific incidence density of hospitalisations due to injuries from dog-bites in Australia for each sex during the study period. Of all Australian states and territories, the lowest rates of 11.64 (95% CI (11.31, 11.97) per 100,000 and 9.57 (95% CI 9.27, 9.87) per 100,000 respectively for males and females were recorded in NSW, followed by 11.68 (95% CI 10.99, 12.37) and 10.21 (95% CI 9.57, 10.85) per 100,000 respectively for males and females in SA. The highest rates of 22.2 (21.04, 23.36) per 100,000 and 18.20 (17.15, 19.25) per 100,000 for males and females respectively were recorded for TAS/ACT/NT. These analyses were solely based on AIHW data.

Table 2.3: State specific incidence density of hospitalisations due to injuries from dog-bites in Australia for each sex, 2001-13

States	Males		Females	
	Cases	ID (95% CI)	Cases	ID (95% CI)
NSW	4778	11.64 (11.31, 11.97)	3991	9.57 (9.27, 9.87)
VIC	4179	13.56 (13.15, 12.97)	3545	11.25 (10.88, 11.62)
QLD	3751	15.23 (14.74, 15.71)	2930	11.84 (11.41, 12.27)
SA	1093	11.68 (10.99, 12.37)	977	10.21 (9.57, 10.85)
WA	1838	14.18 (13.53, 14.83)	1574	12.32 (11.71, 12.93)
TAS/ACT/NT	1410	22.20 (21.04, 23.36)	1152	18.20 (17.15, 19.25)

(Data sourced from AIHW)

Incidence density in each jurisdiction in Australia during the study period 2001-13 is depicted in Figure 2.3, with jurisdictions ordered by population density. The highest rates of 44.64 (41.66, 47.61) were recorded for Northern Territory, followed by 18.75 (95% CI 17.22, 20.27) for the ACT and 12.82 (9%% CI 11.76,13.87) for Tasmania. For this analysis, data from injury surveillance units and data registries of individual states and territories have been used.



(Data sourced from state and territory based data registries and injury surveillance units)

Figure 2.3: State-specific incidence density of hospitalisations due to injuries from dog-bites in Australia for both sexes combined, 2001-13.

2.3.4 National age-specific trends in incidence density

Figure 2.4 presents trends in age-specific incidence density for the study period 2001-13. The incidence density for persons aged 0-4 years or 5-9 years remained roughly stable, but a steady increase in rates was observed for all other age groups after 2003. In sex specific analysis of persons aged 10+ years, the down turn in 2003-05 was more pronounced for males than for females (data not shown).

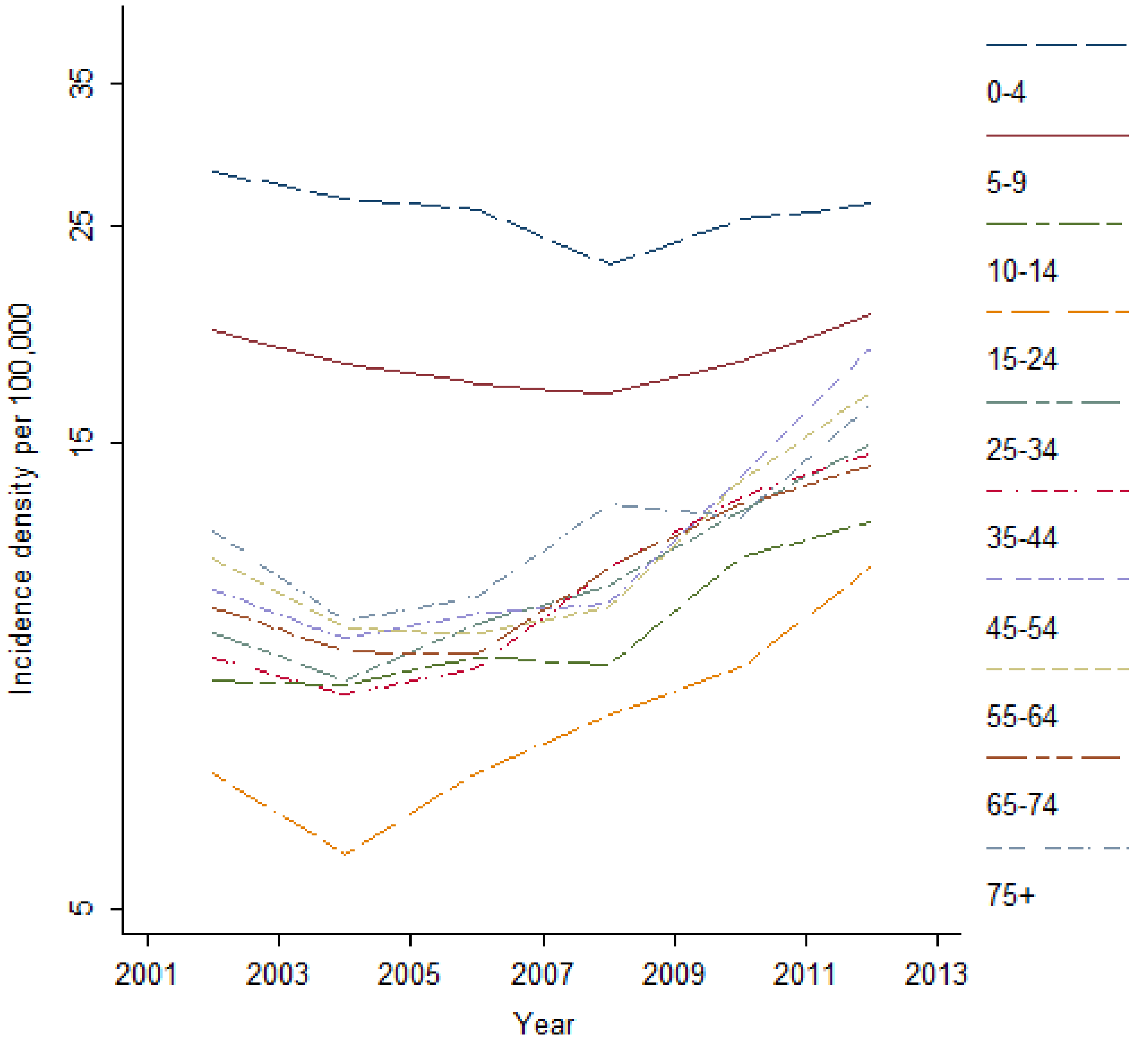


Figure 2.4: Age-specific trends in incidence density, 2001-13

2.4 Discussion

This study has identified a number of patterns in the statistical data for dog-bite injuries in contemporary Australia. On average each year, 2601 persons required hospitalisation for dog-bite injuries in Australia during the study period 2001-13 at an annual rate of 12.39 per 100,000. The highest incidence density was for infants and children aged 0-4 years and the next highest was for 5-9 year olds. Rates for males were higher than those for females for all age groups prior to 45-54 years. Since 2003, there has been a 57% increase in rates that reached 16.15 per 100,000 per year in 2011-13. Of all states and territories, the highest rates were recorded in the Northern Territory. While one would expect growth in the Australian population (which now exceeds 24 million) over time to give a steady rise in the head count of injured people, the concerning aspect is the rising incidence density.

The high incidence and incidence density for 0-4 and 5-9 year olds are consistent with findings of previous national (6) and jurisdictional (1, 9-11) reports. Children are considered to be at a greater risk of dog-bites due to their inexperienced handling of animals (12), their innate curiosity (12-14), and their inability to defend themselves against an animal attack (15) due to their small stature (6).

The excess of male cases in each age category of persons younger than 45 years is consistent with findings from international studies (12, 16), that have reported higher rates of hospitalization due to dog-bites among males. This has been attributed to the greater prevalence of ownership of dogs by men (particularly younger men), the risk-taking tendency of males to be daring and aggressive with dogs, and a predisposition of men to be occupied in professions such as post-carriers, utility meter readers and door-to-door sales persons that have a greater exposure to dog-bites (15).

There are some differences between the estimates of incidence for 2001-03 provided in the national report (6) and the estimates for those years. Most notably, the national report provided estimates for 75+ year olds during 2001-03 were approximately 20% higher than those reported in this study. About half of the cases in that age category during the period covered in the national report were due to being struck by dogs (6). The differences in rates between the national report and this data may be due to the use of WHO ICD classification code ICD-10-AM W54 prior to July 2002. The coding transition from ICD-10-AM W54 to ICD-10-AM W54.0 resulted in restriction to dog-bites as the primary cause of injury requiring hospitalization, and exclusion of injuries from being struck by dogs. This change in coding is likely to be responsible also for the lower incidence density that was reported for 2003-05 than for 2001-03. The more pronounced downturn in rates for males than females between 2001-03 and 2003-05 would be explained if males are more often struck by dogs than females.

The longer-term trends in dog-bite injuries and their underlying driving factors are worthy of comment. The initial decline was followed by a steady increase of 5.9% on average over the remainder of the study period. This pattern was mirrored by increases in age-specific rates for each age category of persons aged 15 years and older, but was not replicated for 0-14 year olds.

The stability in rates of young children relative to those of older individuals may be due to the introduction of successful national and jurisdictional dog-bite prevention initiatives (10) such as Delta Dog safe™, the AVA Pets and People Education Program and SPOT (Safe pets out there) amongst others (17). These programs have generally targeted junior and primary school children. The increases occurred despite the introduction of Domestic Animal Act, the Animal Welfare Act and the Animal Management Act in individual states and territories between 1985 and 2008, and of breed-specific legislation in individual states and territories between 2004 and 2009. The Domestic Animal Act, the Animal Welfare Act and the Animal Management Act provided guidelines for responsible ownership / registration of dogs and prescribed penalties for dog related offenses. Breed-specific legislation identified particular breeds of dogs as being dangerous, and placed restrictions on breeding, handling and ownership of breeds of dogs (18) that could cause serious injury.

The increasing rates were not isolated to specific states. In general, the overall trends were replicated in each state and territory during the study period. The nature of the data for TAS/ACT/NT supplied by AIHW did not permit rates for the Northern Territory, ACT and Tasmania to be calculated separately. For this purpose, data sourced from data registries and injury surveillance units were used. The results showed that the Northern Territory − the jurisdiction with the highest proportion of households exposed to stray dogs (18) − had the highest rates. The next highest rates were recorded in the ACT, followed by Queensland. The lowest rates were for NSW. There is very limited information available on rates of dog ownerships in each state and territory (19) with which to investigate whether the jurisdictional differences in rates can be attributed to jurisdictional differences in dog-ownership.

Several factors may have contributed to the overall increase in rates during the study period. Firstly, there has been an increase in the number of households with dogs. It is estimated that approximately 39% of Australian households now own a dog (19). The Australian Bureau of Statistics online resources indicate that married couples with dependents were most likely of all types of households to have pets, with 49% of those households owning a dog (18). This heightened exposure to dogs as a result of increase in households with dogs may have contributed to the increase in rates over time. Also, an increased awareness of the infectious ramifications of dog-bites (20), and increasing use of surgical procedures to repair damage due to dog-bites (21), may have contributed to a greater number of individuals being treated in Australian hospitals than in previous years.

This study adds considerably to what is known regarding the public health problem of dog-bite injuries in Australia. It is the first national study to report the incidence of hospitalization for injuries due to dog-bites for an extended period with complete coverage of all public hospitals in Australian states and territories. The previous national study covered only a 3-year period. Because the present study is based on the revised ICD-10-AM W54.0 classification (July 2002), it is able to distinguish between injuries from being struck by dogs and injuries due to dog-bites. Furthermore, the restriction to injuries sufficiently serious to require hospitalisation provides a strong focus on important and significant injuries sustained by members of the population, and ensures that the data were based on a distinct criterion (namely hospitalization).

Some limitations of this study must be acknowledged. There was no coverage of dog-bites not treated in public hospitals. An unknown proportion of dog-bites resulting in injuries would have been treated in general medical practice, community health centers, and in private hospitals. The estimates therefore understate the true extent of the problem. The trend data would be unreliable if there has been a systematic shift to or from treatment in general practice or private hospitals during the study period. During 2000-01 to 2009-10, presentations to public hospital emergency departments increased by 1.8% per year (22). A Commonwealth government funding initiative was introduced after 2011 to increase the number of short stay units to accommodate these increasing presentations at the public hospital emergency departments (23, 24). Because this increase in numbers of short stay units occurred during the later stages of this study period, it could not be responsible for the earlier increases. Furthermore, without comprehensive data on dog registrations across Australia, it is not possible to track precisely trends in the rate of increase in dog ownerships or the increase in ownership of specific breeds of dogs. This study provides aggregate level data on the incidence of hospitalization due to injuries from dog-bites in Australia for an extended period, thereby addressing the critical lack of information on this public health problem. It does not attempt to provide individual-level data on minutes or hours of exposure to biting breeds. That will need to come from studies to follow. Finally, it was not possible to provide sex-specific estimates for TAS/ACT/NT due to the aggregated nature of the data supplied by the AIHW.

2.5 Conclusion

In conclusion, there is an increasing public sector burden of hospitalisations for injuries from dog-bites in Australia. This study showed that persons aged 0-4 and 5-9 years had the highest rates of hospitalisation. Prevention initiatives targeting children may have warded off the increases in rates experienced by those aged 15 years or greater, which occurred despite breed-specific legislation in Australia to regulate breeding and ownership of dangerous dogs. Uniform and more complete surveillance of injuries and hospitalisations due to dog-bites and dog ownership would provide evidence for the development of improved public policy in respect of dog-bites. To estimate the total burden from dog-bite related injuries, further research that gathers information on hospital costs, length of stay, quality of life, and return to work is required.

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Chapter 3: Bite-mark analysis – a path forward

Preface

Bite-mark evidence has been used in legal proceedings since at least 1692 but, recently, bite-mark analysis has been subject to substantial criticism. One of the most critical and influential reports has been the National Academy of Sciences report of 2009 ‘ Strengthening Forensic Science in the United States: A Path Forward ‘ commonly called the NAS Report. It was critical to address the limitations of bite-mark analysis, and to recommend a way forward. The following chapter address the fundamental limitations identified by the NAS, and recommends the use of 3D imaging techniques in bite-mark analysis.

3.1 Introduction

Forensic odontology is an established field that deals with the handling, examination and presentation of dental evidence for legal purposes (1-4), primarily in identifying deceased individuals both independently and in conjunction with other biological identifiers such as DNA and fingerprints (3, 5-11). Dental evidence can be used to assess the approximate age, sex, ethnicity, possible occupation, previous dental history and socio-economic status of deceased or unidentified persons for medico-legal reasons (3, 12, 13). In addition, there is potential to identify the animal responsible for a bite from the evidence of its bite-mark, including human perpetrators in violent crimes such as child abuse, sexual assaults and homicide (14-19). The presumption has been that their dentition and its landmark features are unique to an individual (20, 21) and that, when teeth come in contact with skin during the biting process, the resultant bite-mark produced on skin retains sufficient information on landmark features to allow comparison to the suspect's dental features for the purpose of identifying the perpetrator.

3.2 Legal criticisms of bite-mark analysis

Bite-mark evidence has been used in legal proceedings since 1692 (22) but, recently, forensic investigation of bite-marks and other pattern-matching disciplines has been subject to substantial criticism by critical reports from judicial review groups (23). In the USA, there have been 24 cases in which the conviction of an individual based on bite-mark analysis has been overturned as a result of DNA evidence (24). In 11 of the 24 cases that were overturned, the original convictions were based solely on bite-mark evidence. The forensic odontologists involved in each case had reported that the dentition of the suspect was unique, and that the bite-marks matched the suspect dentition perfectly in 13 cases or that the unique features found on the suspect dentition could be identified from the bite-marks in the remaining 11 cases. In almost all of the cases, the forensic odontologists who had examined the bite-mark evidence subsequently reported that they were convinced to a reasonable degree of scientific certainty that the bite-marks found on the victims were made by the suspected perpetrator. The overturn of these convictions and the criticisms that followed have led to calls for suspension of bite-mark analysis as evidence until its scientific credibility can be established (25), and even to recommendations to discontinue the use of bite-mark evidence in criminal investigations in the US (26).

In Australia, two well-cited and heavily-critiqued bite-mark cases are those of Lewis v The Queen (1985) (27, 28) and R v Carroll (2000) (29). In both of these cases, the forensic odontologists who initially examined the bite-mark evidence subsequently reported that the bite-marks matched the suspect dentitions perfectly. These two cases have contributed to the ongoing criticisms surrounding the use of bite-mark evidence in Australia but, to date, this has not led to recommendations to disallow bite-mark evidence in the Australian court system.

3.3 Scientific criticisms of bite-mark analysis

Bite-mark analysis had been subject to scientific criticism in the past (30), but the strongest was yet to come. In 2006, the National Academy of Science (NAS) was commissioned by the United States Congress to conduct an enquiry into the scientific basis of forensic evidence. This enquiry materialized as a result of re-examination, by the The Innocence Project Inc (24), of convictions that had been overturned following judicial review of evidence from subsequent DNA testing (31). Together with cases using evidence from other pattern matching disciplines, the NAS reviewed the cases in which the results of bite-mark analysis were presented as expert evidence in US legal cases, including those where convictions were based solely on bite-mark evidence.

In its report published in 2009, the NAS identified three fundamental limitations of bite-mark analysis. These were that the uniqueness of human dentitions was yet to be established, that the ability of the human skin to retain faithfully in a bite-mark the impression of the biting dentition was yet to be confirmed, and that the type, quality, and number of characteristics required to match a bite-mark to those of a suspect dentition were yet to be determined (32).

3.3.1 Uniqueness of dentitions

Forensic odontologists have claimed that bite-marks created as a result of biting dentitions making contact with skin can be matched to their source because dentitions are unique (33, 34). There is very little evidence to support that claim. Uniqueness of characteristics can be ascertained only when the characteristics have been assessed of all individuals who have existed in the past, exist in the current time period or will exist in the future (35). Aiming to prove uniqueness is pointless because it is not feasible to observe all target objects (33). Other pattern-matching disciplines have also been subjected to criticisms due to the inability of the practitioners to demonstrate uniqueness of the patterns being matched. An example is fingerprint analysis. Finger prints were once considered to be unique, but the Mayfield case (36) serves as a reminder that this is not the case. If its value was conditional on uniqueness, finger-print analysis would be a defunct science. Despite the inability of finger-print experts to demonstrate uniqueness, finger-print evidence continues to be used in courts because its probative value as supportive evidence is greater than that of other forms of evidence such as eye-witness testimony that are still permitted in courts (37). It contributes to building a more comprehensive case and thereby to strengthening the totality of the evidence. Even if dentitions are not unique, there may be cases where bite-marks can have probative value as supporting evidence. More than this, bite-mark evidence may be of specific value in excluding individuals from the pool of suspects (for example, when the dentition of a suspect is complete but it is obvious from the bite-mark that the perpetrator has one or more teeth missing, or vice versa). Bite-mark analysis in such cases has much to offer, and to discard it as an invalid science because of the inability of forensic odontologists to demonstrate uniqueness of dentitions would be unwarranted.

3.3.2 Transfer and retention of identifying information in the bite-mark

Forensic odontologists have claimed that bite-marks can be traced to their source with a reasonable degree of medical certainty (33). Bite-marks on skin occur as a result of contact between teeth and skin, but there are two issues involved. The first is whether or not the pattern of a biting dentition is transferred completely to the skin during a biting episode (32). The issue of relevance is the level and accuracy of detail transferred to the bitten surface. Because bite-marks are an incomplete representation of the biting dentition with impressions only of the anterior biting dentition represented in the bite-mark, the details transferred to the skin need to be clearly discernible and able to be accurately recorded.

The second issue is that of the representational accuracy of dental detail retained on the bitten surface. Over the years, several authors have identified distortion as an important limitation that alters the evidentiary value of bite-marks (38-41). Tissue distortions occur due to biomechanical properties that result in stretching of the skin during the biting episode and its subsequent relaxation after the biting episode (42). Upon removal of the stimulus, in this case the biting force, the skin tends to revert to its original state. This is accompanied by fading of the details of the bite-mark. These changes result in time-related distortions. Photographic distortions occur due to the use of faulty photographic techniques. It is crucial to take suitable steps to determine the extent of tissue distortions, minimise time-related distortions and eliminate distortions associated with faulty photographic techniques and impression-making techniques.

3.3.3 Lack of methodological rigour

The third fundamental issue identified in the NAS Report was the lack of objective criteria with which to ascertain a match between a dentition and a bite-mark. These criteria would include requirements in terms of the type, quality, and number of dental features involved in a match. Because the report is critical of failings more generally to control and quantify error in bite-mark analysis, the author surveys all such issues in this section.

3.3.3.1 Paucity of knowledge on type, quality and number of features that need to be identified in bite-marks

The anterior dentition from the first premolars of one side to the first premolars of the contralateral side are most commonly responsible for bite-marks (9, 43). Among the components of the anterior biting dentition, inter-canine distances are considered to be key features to be examined when analyzing bite-marks (44). However, limited research has been conducted on identifying other features that need to be compared and matched during bite-mark analysis. Whether some dental characteristics have greater evidentiary value than the others is unknown.

The quality with which individual characteristics of a suspect dentition are represented in the bite-mark impression is considered to be important in determining the evidentiary value of the results of bite-mark analysis (45), but a standard for the quality of individual dental features that is required in matching bite-marks with suspect dentitions is yet to be established.

There is limited knowledge about the minimum number of features that is needed for comparing and matching bite-marks with those of the suspect dentitions (46). The general consensus amongst forensic odontologists is to rely on the quality of the bite-mark rather than the number of features examined (47). However, even if dentitions differ between individuals, it is possible that some parts of those dentitions are identical. As an example, if two individuals share a common dental feature such as inter-canine distances, it would not be possible to correctly distinguish one individual from the other if inter-canine distances are the only features that are recorded and examined. Clearly, it is important to examine and compare a large number of features when matching bite-marks to the biting dentition of the suspect, but there is no guidance on what number of features is adequate.

3.3.3.2 Measurement error

In forensic science, errors can result from a number of different sources (48). Inherent errors of measurement as a result of the limitations of measuring instruments or the lack of skill or attention of the observer may affect bite-mark analysis. To minimize errors from this source, there may be need to adopt or develop improved instruments, materials, techniques and procedures. This requires an assessment to be made of the reliability and validity of all measurements made. A case in point is the recording of bite-marks and suspect dentitions. Impression-making and photographic techniques are standard methods (9). Although the ABFO recommends the use of rubber-based impression materials (49), there is limited knowledge of the quality of detail able to be recorded by the different materials that can be used for this purpose. There may be variability amongst forensic odontologists in selecting impression materials based on their availability or preference, and also in the use of those impression materials. In respect to photographic techniques, there is little understanding of intra-operator and inter-operator reliability when photographing bite-marks or when using image-enhancing programs employed in bite-mark analysis (9).

3.3.3.3 Errors of matching

There may be errors associated with matching bite-marks to the biting dentition of a suspect. Even if such errors cannot be eliminated, they may be able to be minimized and quantified. Error rates are indicative of the accuracy of the methods (48), but these are rarely measured probably because it would require duplication and/or repetition of procedures. There is a lack of research on the accuracy of methods that are currently used in matching bite-marks with suspect dentitions. The inter-operator reliability of forensic odontologists in matching bite-marks with biting dentitions made by forensic odontologists has been tested to some extent (6), and has been found to be adequate only. The assessment of intra-operator reliability in matching bite-marks with the biting dentition of suspects is unexplored. In routine casework, it may not be feasible to routinely assess intra-operator and inter-operator reliability of bite-mark matching because only one impression of a bite-mark is usually made. Conducting replicate studies would be challenging, but to do so is critical in establishing reliability within and between practitioners. A difficulty is that there may be loss of surface detail when attempting to create a replicate cast of the bite-mark. It would be useful to identify tools that have the potential to record bite-marks and suspect dentitions in formats that can be shared between assessors quickly and easily to facilitate the assessment of inter-operator reliability.

3.3.3.4 Bias

Systematic errors in bite-mark analysis may occur as a result of measurement inaccuracies or the subjective input of forensic odontologists (50). Such error due to methodology can be quantified for most analytical processes (51) if a "gold-standard" is available, but that is rarely the case in forensic odontology. Limited research has been conducted on bias due subjective judgements and their effect on interpretation of bite-mark evidence (52). The focus must be to quantify bias (55) and to assess the effect of that bias on the analysis and interpretation of the evidence (56). Although bias in the use of conventional techniques may not be able to be completely eliminated, it can be minimized by carefully designing methods that are used in collecting and analyzing bite-mark evidence (54).

3.3.3.5 Non-standardization of methods

The American Board of Forensic Odontology (ABFO), which is the global authority on bite-mark analysis, has set guidelines for conducting bite-mark analysis and has made recommendations on materials that need to be used, and photographic techniques that need to be followed, by forensic odontologists when recording bite-marks and suspect dentitions (53). However, because of the broad range of materials and methods available to record and analyse bite-marks, there are inconsistencies in the manner in which bite-mark analysis is practiced. If current practices are to be retained, there needs to be evidence-based protocols and procedural guidelines to facilitate consistency. But there may be a better path forward to improve on current practices.

3.4 Non-invasive high-resolution 3D imaging in bite-mark analysis

With the number of human and non-human bite-mark cases on the rise (55, 56), it seems important to be able to retain forensic guidance from bite-mark analysis. The aim of this article is recommend a novel approach to address the fundamental limitations of bite-mark analysis and to strengthen the credibility of bite-mark evidence.

Recent technological advances in 3D imaging offer an opportunity to remedy some of the weaknesses currently associated with bite-mark analysis. The new generation of portable, non-invasive intra-oral 3D scanners, that are currently used as an alternative to conventional dental impression materials in clinical dentistry, have made the process of acquiring dental impressions faster and easier (57-59). Modern imaging technology permits recording of bite-marks and the dentitions of suspected perpetrators in three dimensions, and extraction of measurements of key landmark features from the 3D images is possible using software supplied with the scanning tools. In what follows, the author explains how 3D imaging can assist to overcome the three fundamental limitations of bite-mark analysis that were identified in the NAS report.

3.4.1 Quantification of variation in animal dentitions using 3D imaging tools

Currently there is no repository of information that can be used as a reference system for quantifying population variation in dentitions of biting animals such as those of humans and dogs. Three dimensional imaging tools provide images of bite-marks that are of high resolution, and the technology allows researchers to collect, store and share large numbers of 3D images of dentitions and bite-marks. This makes possible the compilation of images of the dentitions of biting animals in databases. Compilations of images would be made not in the vain hope of establishing the uniqueness of dentitions, but rather to quantify variation in landmark dental features. This may one day make possible probabilistic statements such as "only 0.3% of dogs and no full breeds other than German Shepherds have a maximum inter-canine distance of 40.10mm and a canine crown length of at least 17.25mm". Such statements would qualify appropriately the probative value of evidence from a bite-mark analysis, and help to re-establish its credibility.

3.4.2 Contending with distortion using 3D imaging tools

To establish a match between a bite-mark and a suspect dentition correctly, it is critical to take into account the amount of distortion that may have occurred. Very little research has been conducted on distortion. There is an urgent need to investigate the various types of distortions that can be present in a bite-mark and the images of it, and to take steps to minimise them. Distortions associated with invasive impression-making techniques that are currently used in bite-mark analysis can be eliminated by 3D scanning, which is a non-invasive image-capturing procedure that requires no contact with the surface on which the bite-mark is registered. Distortions associated with 2D photographic techniques are eliminated also by using 3D scanning methods to record information in 3D space. The high resolution of the 3D scanners also facilitates image capture without the need of ABFO No 2 scales for reference as recommended by the ABFO (49). Tissue distortions defy bite-mark matching using current methods, but accurate recording of the positional location of key features in the bite-mark using 3D tools is a starting point, and in future sophisticated mathematical analysis of the relative location of the marks of key features may be able to establish a probabilistic match with a suspected dentition or at least eliminate other candidate dentitions. The ability of 3D imaging tools to record 3D images of bite-marks accurately, and the capacity to move images in 3D space, offers the future possibility of quantifying tissue changes such as stretching and displacement in three dimensions. The use of 3D imaging tools can assist in accurate modelling of time-related distortions by permitting recording of bite-marks in three dimensions at different time intervals. Neither of these is possible using 2D photographic methods.

3.4.3 Improving methodological rigour using 3D imaging tools

Because of their ability to be moved in 3D space, 3D images have the potential to facilitate measurements of a larger number of characteristics and landmark features than those possible by impression-making and 2D imaging techniques currently used in bite-mark analysis. Depending on the detail transferred in the bite-mark, this would allow the number and range of features required for a match to be established between a dentition and a bite-mark to be expanded. In these studies, the author has demonstrated that it is possible to measure and examine a large number of landmark dental features from 3D images (110 in human dentitions and 158 in dog-dentitions), with the potential to include more features if required.

Using 3D scanners to record dentitions and bite-marks has the potential to remove or at least reduce random observer error, and to minimize bias. Previous studies have demonstrated that 3D image capture is more precise than the 2D photographic technique (60). Our own work has shown that the intra-oral 3D scanner can be used to record and measure dentitions reliably and accurately (61). The author has shown that there is minimal intra- and inter-observer error in the use by trained operators of either digital hand-held calipers or 3D scanning tools, but the difference is that 3D scanning minimizes subjective inputs and removes the possibility of bias from that source in the measurement process. The errors in matching bite-marks to dentitions have never been studied explicitly, but our proof-of-concept study (62) raises the possibility that bias can be avoided altogether by the use of 3D imaging technology. The process of matching 3D images of bite-marks with those of the suspect dentition has the potential to be automated. Automating the matching process may remove all requirements for subjective inputs from forensic odontologists, and hence minimize bias associated with bite-mark analysis. This proof-of-concept study also demonstrated that the accuracy of matching was conditional on which key dental features are recorded in the bite-mark, and laid a path towards establishing standards for accurate and quantitative assessment of the evidence in a bite-mark.

3.5 Recommendations

This section outlines research recommendations aimed at strengthening the scientific credibility of bite-mark analysis. Some of this research has been commenced by the authors of this paper (61, 62). However, there is more that needs to be done.

3.5.1 Primary recommendation

3.5.1.1 Use of 3D scanning

The author's primary recommendation is that, wherever possible, 3D scanning should be used in recording bite-marks for forensic examination. The author recommends the placement of 3D scanners in emergency departments and ambulances as standard equipment. A previous study has shown that bite-mark indentations on skin typically disappear after 30 minutes (38). In these studies, the author demonstrated that teeth or impressions of teeth of both the upper and lower dental arches can be scanned in less than 6 minutes. Making 3D scanners available at the point of first contact with emergency services would facilitate swift and accurate recording of bite-marks.

3.5.2 Other recommendations

3.5.2.1 Compilation of databases of scans of dentitions of biting animals using 3D imaging

The author recommends developing globally expandable and accessible databases of 3D images of the dentitions of biting animals that can be consulted to quantify variations in dental characteristics. The author also recommends developing databases of 3D images of bite-marks that can be consulted during bite-mark analysis.

3.5.2.2 Research to quantify distortions using 3D scanning tools

The author recommends scanning and recording actual bite-marks on human skin as they are presented to emergency services and, if possible, with the scanning repeated at regular intervals. This would require emergency department staff to be trained to scan bite-marks, and released from other duties to do so, while the victim is under emergency care. Whilst this might not be possible for severely-injured persons and particularly for those with multiple injuries, it may be feasible in some cases. This would allow accumulation of images over time, even if the rate of accumulation is slow due to competing priorities within the emergency department.

The author recommends research into tissue and time-related distortions using these 3D images. By setting up a central repository of 3D images of bite-marks, all scanned images from emergency departments could be transferred to the central repository. These images would then be examined by researchers to investigate tissue and time-related distortions in bite-marks as they present in real-life cases.

The author recommends interim investigations of time-related distortions using the 3D imaging techniques. This can be done by creating experimental bite-marks on pig skin and assessing the amount of information available or lost by scanning bite-marks at different time intervals using the IntraScan intra-oral 3D scanner and measuring landmark dental features on 3D images of bite-marks. This may be repeated on pig skin with bite-marks that are exposed to different temperatures, that are covered by different types of clothing and that are immersed under water to assess the effect of these factors on the distortion of bite-marks.

3.5.2.3 Research to quantify and rectify error using 3D scanning tools

The author recommends assessment of the reliability and validity of measurements made with other intra-oral 3D scanners to allow generalisation of the findings for the Zfx IntraScan intra-oral 3D scanner (61). For standardizing the scanning process, the author recommends training programs for operators on the appropriate use of intra-oral 3D scanners.

The author recommends further research on differentiating dental features of dogs based on their breed, age and sex. A proof-of-concept for dog dental arches has been presented (62) but no confirmation that it is possible to discriminate between dogs of the same breed but different sex and age. This can be achieved by extending the proof-of-concept study to include dogs of known breeds, ages and sexes. In future, this research would be extended to human bites when sufficient images of human bites have been collected in the central repository.

The author recommends further research on investigating and establishing standards for the quality of individual dental characteristics required to demonstrate that the results of a bite-mark analysis are of evidentiary value. This can be achieved by examining the contribution of various individual dental characteristics in establishing matches. The author has demonstrated the feasibility of this approach in their proof-of-concept study (62).

As part of a future agenda, the author recommends research on automating the process of measuring and matching of landmark dental features found on bite-marks with those of the dentition of a suspect. This may be achieved by identifying or developing, and validating, software that allows superimposition of 3D images of bite-marks on those of suspect dentitions as a means of establishing matches, potentially eliminating the role of the operator altogether.

3.6 Conclusion

As currently practiced, bite-mark analysis has significant scientific limitations. The use of 3D technology provides prospects of overcoming or minimizing these limitations and the author recommends that this technology be universally adopted in forensic investigations of bite-marks. Additionally, the author has made recommendations for further research designed to refine and enhance the use of the technology, and ultimately to strengthen the scientific credibility of bite-mark analysis. Bite-mark evidence produced using scientifically valid techniques would have probative value as supporting evidence to build a prosecution case (47), allowing courts to consider corroborating evidence when reaching decisions (63).

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Chapter 4: The reliability and validity of measurements of human dental casts made by an intra-oral 3D scanner, with conventional hand-held digital callipers as the comparison measure

Preface

Prior to using 3D scanning tools in bite-mark analysis, the reliability and validity of measurements of landmark dental features, made with an intra-oral 3D scanner had to be investigated. Chapter 4 discusses the steps involved in assessing the reliability and validity of measurements of landmark dental features made with an intra-oral 3D scanner with a handheld digital caliper as a comparison measure.

4.1 Introduction

Measurements of landmark dental features of teeth and dental casts have been made for research and diagnostic purposes (1-8). Dental anatomy is considered to be of great value in a wide range of anthropological, dental and forensic applications (9), including bite-mark analysis (5). Traditionally, in forensic investigations, dental casts of suspected perpetrators are compared with bite-marks in an attempt to establish the source of the bite (10, 11). The results of such comparisons have been used as evidence in courts of law (10, 12-16).

However, dental casts are bulky (17, 18) and may undergo structural and chemical changes during the various stages of the casting procedure (19), leading to geometric and dimensional inconsistencies between real teeth and their plaster replications (20). Such geometrical inconsistencies may result in inaccurate measurements of landmark dental features as a consequence. Long term storage and stability of casts is also an issue.

Digital scanning, 3D impression techniques and digital scanners have been used to create virtual digital models that can be used in dentistry and other related fields (10, 12-16, 21). Several studies have compared standard measurements of dental landmarks made from dental casts with their virtual counterparts. These studies have concluded that the measurements made using 3D scanners are accurate and reliable for therapeutic purposes (22, 23). As a result, chair-side 3D scanners are considered to be a reliable alternative to conventional impressions for fabricating crowns, bridges and dental appliances (22, 24-28). 3D scanners for impressions and dental casts have traditionally been large desktop devices, but in recent years a new generation of portable intra-oral 3D scanners have been introduced for use in dentistry. They have made the process of acquiring virtual dental impressions faster and easier (27, 29). The portable intra-oral 3D scanners have the potential to allow researchers to collect, store and share digital images of large numbers of dentitions, and they provide also the capability of recording impressions such as indented bite-marks if the indentations are scanned before they disappear.

Despite their acceptance as an alternative to conventional impression-making techniques in mainstream dentistry, the use of intra-oral 3D scanners in forensic investigations is relatively unexplored. The aim of this study was to assess the reliability and validity of measurements of human dental casts made with digital callipers versus measurements from digitized versions of the same casts created using a portable intra-oral 3D-scanner. The results would have influence in determining whether the device is appropriate for recording dentitions for research and forensic purposes.

4.2 Methods

4.2.1 Dental casts

De-identified human dental casts were obtained from five orthodontic practices in Launceston, Tasmania. Dental casts for this study were collected after appropriate Human Research Ethics Committee clearances were obtained (HREC number: H0013427). From tables provided by Walter et al (30), it was determined that a sample size of 46 would provide 80% power (two-sided $\alpha = 0.05$) to detect an estimated ICC of 0.9 as being different from a benchmark value of 0.8. Based on that estimate, a total of 50 upper and 50 lower diagnostic study models were selected from a pool of 80 sets of dental casts. The casts were eligible for selection if they satisfied the following selection criteria: no missing permanent teeth up to second molars in both upper and lower arches, no visible blebs or air bubbles on the measuring surfaces of the casts, no physical damage to the teeth on the dental casts and no evidence of dental appliances, fillings, crowns and implants with crowns or bridges on the dental casts. The casts included in the study were selected from the eligible casts using the online tool Research Randomiser® (31).

4.2 2 Digital modelling

After an initial learning phase with the scanning device that was completed over two weeks, the selected dental casts were scanned using a portable Zfx™ IntraScan intra-oral 3D scanner (Zfx™ IntraScan, Zfx GmbH, Dachau, Germany) to produce a virtual 3D model of each cast. Each virtual 3D model was made by scanning the physical casts for approximately 3 minutes. All scans were made at ambient room temperature. The scanner was given a cooling-off period of 5-10 minutes between consecutive scanning of dental casts. The scanner was calibrated prior to each scan to standardise the scanning process. The supporting software supplied with the scanner was used to view each virtual model on a 17-inch LCD computer monitor with a screen resolution of 1366 x 768 pixels. The resultant 3D virtual dental models were securely stored on University of Tasmania internal servers in .stl file format with access restricted to the research team.

4.2.3 Measurements

Two raters each independently measured a total of 55 landmark dental features on each of the upper and lower dental cast combinations (110 measurements in total), first to the nearest 0.01mm using an electronic hand-held digital calliper (Mitutoyo® Digimatic calliper) applied to each of the upper and lower physical dental casts, and secondly using the onscreen measuring tool that is part of the supporting software provided with the Zfx IntraScan intra-oral 3D scanner on the corresponding virtual 3D dental casts. Measurements were repeated by both raters at least one-week later using each method. The features measured are referred to by abbreviations that are listed in the Supplementary Table 4.1.

The 55 measurements included 14 crown lengths, 14 bucco-lingual measurements, 14 mesio-distal measurements and 13 arch measurements for each dental cast. The operational definitions of dental features measured for this study were consistent with measurement methods outlined in previous studies. The arch widths measurements were as defined by Foster et al (32), Lavelle et al (33) and Lavelle et al (34); inter-canine widths were as defined by Cohen (35), Burson (36), Moorrees (37), Lavelle and Foster (38) and Grewe (39); mesio-distal measurements were based on the definitions of Barrett et al (40); bucco-lingual measurements were consistent with definitions of Barrett et al (41); and crown length measurements were based on the definition of Bjorndal et al (42). These 55 landmark features are standard dental measurements that have been used in odontometry and were selected for this study to provide a representative coverage of the entire dentition.

4.2.4 Analytic approach

Repeated measurements of tooth crowns and arch widths were made firstly by hand-held callipers applied to the physical dental casts, and secondly by using the virtual onscreen measuring tool applied to the virtual 3D dental casts, and were assessed for inter-method validity and inter-rater and intra-method/rater reliability. Reliability and validity were assessed by: a) calculation of means of method-method or rater-rater differences; b) inspection of Bland-Altman plots; c) regression of absolute and signed values of the differences on covariates for factors that may influence reliability and validity (crowding, rotation, presence of extra cusps, and malocclusion recorded as present or absent with respect to each tooth, and eruptions (with teeth that were not completely erupted recorded as partially erupted); d) calculation of standard error of measurement (SEM); and e) calculation of intra-class correlation (ICC) coefficients for inter-method, inter-rater and intra-method/rater comparisons.

The concurrent assessment of inter-method validity and inter-rater and intra-method/rater reliability in this three-factor (subjects, methods, raters) with replication design was carried out by extending the approach of Eliasziw et al (43) for two factors with replication. The two factor approach of Eliasziw et al (43) allows simultaneous assessment of reliability between and within raters. This extension to three factors allows simultaneous assessment of reliability within methods and raters and of validity between methods.

Let x_{ijkl} denote the l^{th} measurement taken by the k^{th} rater using the j^{th} method on the i^{th} subject where $i = 1, 2, \ldots I$, $j = 1, 2, \ldots J$, $k = 1, 2, \ldots K$ and $l = 1, 2, \ldots L$. The following linear model was assumed for the x_{ijkl}:

$$x_{ijkl} = \mu + a_i + b_j + c_k + (ab)_{ij} + (ac)_{ik} + (bc)_{jk} + (abc)_{ijk} + \varepsilon_{ijkl}$$

where μ is the fixed population mean, $a_i = X_i$ are the departures from μ of the targets' true scores X_i, $b_j = \bar{x}_j - \mu$ are the departures from μ of the mean $\bar{x}_j$ of the measurements made using the j^{th} method, and $c_k = \bar{x}_k - \mu$ are the departures from μ of the mean $\bar{x}_k$ of the measurements made by the k^{th} rater and ε_{ijkl} is the error term. The interaction terms $(ab)_{ij}$, $(ac)_{ik}$, $(bc)_{jk}$ and $(abc)_{ijk}$ represent departures of the mean of measurements for each combination of factors (subjects, methods, raters) from the value expected based on the means of the factors involved. The specific distributional assumptions made were that the subject variations a_i, the method variations b_j, the rater variations c_k, the subject-method variations $(ab)_{ij}$, the subject-rater variations $(ac)_{ik}$, the method-rater variations $(bc)_{jk}$, the subject-method-rater variations $(abc)_{ijk}$, and the error ε_{ijkl} are each identically and independently normally distributed with a mean of zero and a variance of σ_a^2, σ_b^2, σ_c^2, σ_{ab}^2, σ_{ac}^2, σ_{bc}^2, σ_{abc}^2 and σ_ε^2 respectively (44). In this formulation, all sources of variation are random. The expected mean squares are tabulated by Snedecor and Cochrane (44).

Using the correlation approach of Eliasziw et al (43), the inter-method ICCs were estimated as:

$$\mathrm{ICC}_{\text{inter-method}} = \frac{\operatorname{cov}\left(x_{ijkl}, x_{ij'kl}\right)}{\operatorname{var}(x_{ijkl})}$$

where $\operatorname{cov}\left(x_{ijkl}, x_{ij'kl}\right)$ is the covariance between measurements made by different methods (here denoted by j and j') and $\operatorname{var}\left(x_{ijkl}\right)$ is the total variance of the x_{ijkl}. Under the model assumptions:

$$\operatorname{cov}\left(x_{ijkl}, x_{ij'kl}\right) = \sigma_a^2 + \sigma_b^2 + \sigma_{ab}^2 + \text{terms of zero expectation}$$

$$\operatorname{var}(x_{ijkl}) = \sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \sigma_{ab}^2 + \sigma_{ac}^2 + \sigma_{bc}^2 + \sigma_{abc}^2 + \sigma_\varepsilon^2$$

and hence:

$$\mathrm{ICC}_{\text{inter-method}} = \frac{\sigma_a^2 + \sigma_b^2 + \sigma_{ab}^2}{\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \sigma_{ab}^2 + \sigma_{ac}^2 + \sigma_{bc}^2 + \sigma_{abc}^2 + \sigma_\varepsilon^2}$$

Similarly:

$$\mathrm{ICC}_{\text{inter-rater}} = \frac{\operatorname{cov}\left(x_{ijkl}, x_{ijk'l}\right)}{\operatorname{var}(x_{ijkl})} = \frac{\sigma_a^2 + \sigma_b^2 + \sigma_{ac}^2}{\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \sigma_{ab}^2 + \sigma_{ac}^2 + \sigma_{bc}^2 + \sigma_{abc}^2 + \sigma_\varepsilon^2}$$

where $\operatorname{cov}\left(x_{ijkl}, x_{ijk'l}\right)$ is the covariance between measurements made by different raters (here denoted by k and k'). We can also define:

$$\mathrm{ICC}_{\text{intra}} = \frac{\operatorname{cov}\left(x_{ijkl}, x_{ijkl'}\right)}{\operatorname{var}(x_{ijkl})} = \frac{\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \sigma_{ab}^2 + \sigma_{ac}^2 + \sigma_{bc}^2 + \sigma_{abc}^2}{\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \sigma_{ab}^2 + \sigma_{ac}^2 + \sigma_{bc}^2 + \sigma_{abc}^2 + \sigma_\varepsilon^2}$$

where $\operatorname{cov}\left(x_{ijkl}, x_{ijkl'}\right)$ is the covariance between the two replicate measurements (here denoted by l and l'). Bootstrapping with 500 re-samples was used to estimate 95% confidence intervals.

4.3 Results

Table 4.1 shows the means of measurements for all 110 landmark features made using the hand-held callipers on the physical dental casts and the virtual onscreen measuring tool provided with the IntraScan Intra-oral 3D scanner on the virtual 3D dental casts. These are averages over two raters and two occasions and almost all are within 0.01mm of the corresponding mean for the other method. The measurements by the measuring tool provided with the scanner were on average slightly higher than the measurements made by the calliper, and higher for just over two-thirds (74/110) of the features.

In data not shown but reported in Supplementary Table 4.2, the highest prevalence of crowding occurred in the central incisors in both the upper and the lower arches. The right lateral incisors had the greatest prevalence of rotations in the upper arch. In the lower arch, the lower left central incisors, the lower right and the left lateral incisors had the highest prevalence of rotations. The maximum number of extra cusps was in the right first molar of the upper arch. In the lower arch, the lower left first molars had the greatest number of extra cusps. The prevalence of malocclusion was the greatest with respect to the right first molars in the upper arch and the lower right first premolars in the lower arch. In the upper arch, the left second molar had the highest prevalence of impacted or unerupted teeth. In the lower arch, the right second molar had the greatest prevalence of partially erupted teeth.

Table 4.1: Means of measurements of landmark dental features made using hand-held callipers and the measuring tool provided with the Zfx IntraScan intra-oral 3D scanner

Feature	Upper		Lower	
	Calliper	Scanner	Calliper	Scanner
Central Incisor Maximum arch width	16.992	16.994	10.582	10.626
Lateral Incisor Maximum arch width	27.618	27.559	20.832	20.817
Canine Maximum arch width	34.240	34.256	25.678	25.692
First Premolar Maximum arch width	44.746	44.642	38.947	38.851
Second Premolar Maximum arch width	49.507	49.407	45.035	45.011
First Molar Maximum arch width	55.302	55.275	52.162	52.118
Second Molar Maximum arch width	61.047	60.981	57.362	57.311
Central Incisor Minimum arch width	2.023	1.878	1.601	1.593
Lateral Incisor Minimum arch width	16.368	16.596	9.424	9.461
First Premolar Minimum arch width	27.741	27.711	25.589	25.592
Second Premolar Minimum arch width	32.459	32.529	29.702	29.701
First Molar Minimum arch width	34.939	34.901	32.642	32.595
Second Molar Minimum arch width	41.843	41.857	38.692	38.676
Right Central Incisor BLD	6.569	6.573	7.741	7.745
Right Lateral Incisor BLD	5.742	5.782	7.677	7.657
Right Canine BLD	7.450	7.465	9.210	9.196
Left Central Incisor BLD	6.408	6.482	7.827	7.853
Left Lateral Incisor BLD	5.759	5.815	7.877	7.910
Left Canine BLD	7.638	7.660	9.144	9.181
Right First Premolar BLD	9.120	9.111	6.777	6.795
Right Second Premolar BLD	9.280	9.271	6.587	6.617
Right First Molar BLD	11.061	11.076	6.128	6.124
Right Second Molar BLD	10.864	10.886	7.791	7.809
Left First Premolar BLD	9.135	9.106	7.774	7.804
Left Second Premolar BLD	9.239	9.233	6.918	6.923
Left First Molar BLD	11.093	11.108	6.596	6.586
Left Second Molar BLD	10.955	10.949	6.258	6.246
Right Central Incisor MDD	8.822	8.871	5.429	5.446
Right Lateral Incisor MDD	6.884	6.920	5.975	6.033
Right Canine MDD	7.842	7.924	6.830	6.841
Left Central Incisor MDD	8.738	8.825	5.427	5.470
Left Lateral Incisor MDD	6.917	6.941	5.929	5.968
Left Canine MDD	7.801	7.821	6.813	6.843
Left First Premolar MDD	7.026	7.088	7.223	7.260
Left Second Premolar MDD	6.764	6.898	7.172	7.207
Left First Molar MDD	10.739	10.745	11.106	11.119
Left Second Molar MDD	9.799	9.841	10.506	10.536
Right First Premolar MDD	6.977	7.016	7.219	7.252
Right second Premolar MDD	6.858	6.934	7.156	7.190
Right First Molar MDD	10.832	10.879	10.968	11.009
Right Second Molar MDD	9.946	9.954	10.321	10.332

Right Central Incisor CL	9.561	9.586	5.477	5.478
Right Lateral Incisor CL	8.172	8.204	5.758	5.776
Right Canine CL	9.123	9.108	6.873	6.897
Left Central Incisor CL	9.691	9.747	5.478	5.527
Left Lateral Incisor CL	8.130	8.189	5.804	5.827
Left Canine CL	9.057	9.162	6.817	6.836
Right Second Molar CL	6.135	6.185	7.753	7.760
Right First Premolar CL	7.453	7.457	8.400	8.389
Right Second Premolar CL	6.476	6.523	10.269	10.262
Right First Molar CL	6.659	6.641	9.916	9.876
Left First Premolar CL	7.545	7.584	7.805	7.793
Left Second Premolar CL	6.653	6.655	8.372	8.383
Left First Molar CL	6.639	6.652	10.246	10.224
Left Second Molar CL	6.379	6.364	9.856	9.847

4.3.1 Inter-method results

Summary information on the differences of means for measurements made using hand-held calliper and the virtual 3D dental casts is reported in Table 4.2. The values shown are those of pairs of measurements by each rater on each occasion. Of all the features measured in both the upper and the lower arches, the smallest difference of means was for the mesio-distal dimensions of the left second pre-molars in the upper arch and the right lateral incisor in the lower arch. The largest difference in means was for the crown length measured on the right canine in the upper arch and the maximum arch widths of the first premolars in the lower arch. As a percentage of the average of the measurements, the percentage difference in means of measurements ranged between 0.030% and 1.134% for the upper arch and between 0.052% and 0.965% for the lower arch. In the upper arch, the lowest percentage difference in means was for the maximum arch widths of the second molars and the highest was for the bucco-lingual dimension of the left central incisor. In the lower arch, the lowest percentage difference in means was for the maximum arch width of the second premolars and the highest was for the mesio-dimensional distance of the right lateral incisor.

Table 4.2: Difference of means for pairs of measurements made using the digital hand-held calliper and the measuring tool provided with the Zfx IntraScan intra-oral 3D scanner

Category of feature*	Upper	Lower
	Diff of means† (SD)	Diff of means† (SD)
Maximum arch width (n=13)		
Low	-0.001 (0.001)	-0.043 (0.010)
Mid	0.058 (0.041)	0.023 (0.030)
High (FPM)	0.104 (0.073)	0.095 (0.067)
Minimum arch width (n=13)		
Low	-0.070 (0.027)	-0.037 (0.002)
Mid	0.029 (0.049)	0.007 (0.011)
High	0.145 (0.103)	0.047 (0.033)
Anterior bucco-lingual dimension (n=14)		
Low	-0.073 (0.002)	-0.048 (0.001)
Mid	-0.039 (0.015)	-0.023 (0.013)
High	-0.003 (0.051)	-0.001 (0.034)
Posterior bucco-lingual dimension (n=14)		
Low	-0.021 (0.004)	-0.010 (0.004)
Mid	0.005 (0.010)	0.008 (0.007)
High	0.029 (0.020)	0.040 (0.028)
Anterior mesio-distal dimension (n=14)		
Low	-0.087 (0.013)	-0.057 (0.008)
Mid	-0.049 (0.025)	-0.039 (0.020)
High	-0.019 (0.061)	-0.011 (0.040)
Posterior mesio-distal dimension (n=14)		
Low	-0.134 (0.004)	-0.047 (0.008)
Mid	-0.046 (0.033)	-0.033 (0.023)
High	-0.006 (0.095)	0.011 (0.033)
Anterior crown length (n=14)		
Low	-0.059 (0.010)	-0.036 (0.003)
Mid	-0.032 (0.022)	-0.025 (0.014)
High	0.149 (0.074)	0.020 (0.026)
Posterior crown length (n=14)		
Low	-0.013 (0.001)	-0.030 (0.002)
Mid	-0.004 (0.010)	-0.004 (0.008)
High (LSM)	0.014 (0.035)	0.012 (0.021)

* Where the same feature provided the lowest (low) or median (med) or highest (high) values for both the upper and the lower arches, this has been indicated in brackets

†Calculated as the difference of the mean of pairs of measurements by hand-held callipers from the mean of pairs of measurements by the IntraScan intra-oral 3D scanner

Summary information on the inter-method SEMs and ICCs is reported in aTable 4.3. For the upper arch, the lowest SEM was for the maximum arch widths of the central incisors and the highest was for the maximum arch widths of the second molars. In the lower arch, the lowest SEM was for minimum arch widths of the central incisors and the highest was for maximum arch width of the second premolars. As a percentage of the average of the measurements of each feature by each method, the SEM ranged between 0.037% and 0.535% for the upper arch and between 0.042% and 0.359% for the lower arch. The inter-method ICC values were uniformly high, ranging between 0.904 and 0.998 for the upper arch and between 0.935 and 0.999 for the lower arch. The highest correlation was for arch widths of both the upper and the lower arches. The highest correlation was for the maximum arch widths of the second molars for both the upper and the lower arches. For the upper arch, the lowest correlation was for the mesio-distal dimension of the right second premolars. For the lower arch, the lowest correlation was for the bucco-lingual dimension of the right first premolars.

Table 4.3: Inter-method SEM and ICC for measurements made using the digital hand-held calliper and the measuring tool provided with the Zfx IntraScan intra-oral 3D scanner

Category of feature*	Upper		Lower	
	SEM	ICC (95% CI)	SEM	ICC (95% CI)
Maximum arch width (n=13)				
Low (CI)	0.017	0.984(0.980,0.987)	0.008	0.982(0.979,0.986)
Mid (FPM)	0.026	0.996(0.996,0.997)	0.018	0.994(0.993,0.995)
High (SM)	0.037	0.998(0.998,0.998)	0.029	0.999(0.999,0.999)
Minimum arch width (n=13)				
Low (LI)	0.020	0.949(0.889,0.998)	0.001	0.984(0.981,0.988)
Mid	0.025	0.995(0.993,0.998)	0.018	0.996(0.995,0.996)
High	0.046	0.997(0.996,0.998)	0.023	0.997(0.996,0.998)
Anterior bucco-lingual dimension (n=14)				
Low	0.014	0.943(0.932,0.954)	0.007	0.955(0.947,0.962)
Mid	0.021	0.963(0.954,0.971)	0.008	0.972(0.966,0.978)
High	0.031	0.989(0.985,0.992)	0.014	0.983(0.978,0.988)
Posterior bucco-lingual dimension (n=14)				
Low (FPM)	0.007	0.939(0.928,0.950)	0.008	0.935(0.918,0.952)
Mid	0.015	0.966(0.958,0.974)	0.012	0.967(0.961,0.973)
High	0.021	0.980(0.975,0.984)	0.019	0.981(0.975,0.987)
Anterior mesio-distal dimension (n=14)				
Low	0.012	0.918(0.901,0.934)	0.007	0.938(0.927,0.949)
Mid	0.013	0.941(0.931,0.952)	0.009	0.945(0.937,0.952)
High	0.020	0.947(0.935,0.958)	0.014	0.960(0.951,0.969)
Posterior mesio-distal dimension (n=14)				
Low	0.012	0.904(0.890,0.919)	0.007	0.957(0.951,0.963)
Mid	0.014	0.941(0.927,0.956)	0.009	0.971(0.958,0.985)
High	0.022	0.984(0.976,0.993)	0.013	0.982(0.979,0.986)
Anterior crown length (n=14)				
Low (RCI)	0.012	0.986(0.983,0.989)	0.009	0.988(0.986,0.990)
Mid	0.014	0.988(0.984,0.991)	0.010	0.991(0.989,0.993)
High	0.020	0.991(0.989,0.993)	0.012	0.995(0.994,0.996)
Posterior crown length (n=14)				
Low (RSM)	0.011	0.969(0.951,0.986)	0.006	0.972(0.959,0.985)
Mid	0.017	0.982(0.978,0.986)	0.011	0.983(0.979,0.987)
High	0.032	0.986(0.984,0.988)	0.022	0.990(0.988,0.992)

*Where the same feature provided the lowest (low) or median (med) or highest (high) values for both the upper and the lower arches, this has been indicated in brackets

4.3.2 Inter-rater results

The SEMs and ICCs for measurements by the two raters are reported in Table 4.4. As a percentage of the average of the measurements of each feature by each rater, the SEM ranged between 0.016% and 0.174% for the upper arch and between 0.009% and 0.166% for the lower arch. The SEMs on average were only one-half of inter-method values. All inter-rater ICCs were greater than 0.959 for both the upper and the lower arches. The highest ICCs were for the arch widths of both the upper and the lower arches and the lowest ICCs were for the right and the left central incisors of the upper and the lower arches respectively.

Table 4.4: Inter-rater SEM and ICC for measurements made using the IntraScan intra-oral 3D scanner and the digital hand-held calliper

Category of feature*	Upper		Lower	
	SEM	ICC (95% CI)	SEM	ICC (95% CI)
Maximum arch width (n=13)				
Low (CI)	0.004	0.992(0.990,0.995)	0.002	0.993(0.992,0.994)
Mid	0.006	0.998(0.997,0.998)	0.003	0.996(0.994,0.997)
High	0.008	0.999(0.999,0.999)	0.014	0.999(0.999,0.999)
Minimum arch width (n=13)				
Low (LI)	0.002	0.959(0.942,0.976)	0.001	0.997(0.996,0.997)
Mid	0.016	0.982(0.974,0.989)	0.004	0.998(0.997,0.999)
High (FPM)	0.033	0.999(0.999,0.999)	0.017	0.999(0.999,0.999)
Anterior bucco-lingual dimension (n=14)				
Low (LC)	0.004	0.982(0.973,0.990)	0.003	0.987(0.982,0.991)
Mid	0.006	0.990(0.987,0.994)	0.004	0.988(0.986,0.990)
High	0.013	0.995(0.994,0.996)	0.006	0.989(0.987,0.990)
Posterior bucco-lingual dimension (n=14)				
Low	0.003	0.978(0.974,0.982)	0.003	0.979(0.971,0.987)
Mid	0.006	0.986(0.984,0.988)	0.006	0.982(0.978,0.986)
High	0.010	0.995(0.994,0.996)	0.008	0.989(0.988,0.991)
Anterior mesio-distal dimension (n=14)				
Low	0.005	0.964(0.956,0.972)	0.003	0.970(0.965,0.975)
Mid	0.006	0.977(0.974,0.981)	0.005	0.976(0.973,0.980)
High	0.007	0.988(0.985,0.990)	0.009	0.984(0.981,0.987)
Posterior mesio-distal dimension (n=14)				
Low	0.003	0.967(0.962,0.971)	0.003	0.979(0.976,0.982)
Mid	0.005	0.974(0.971,0.977)	0.005	0.986(0.983,0.988)
High	0.007	0.992(0.991,0.994)	0.007	0.993(0.992,0.995)
Anterior crown length (n=14)				
Low	0.005	0.992(0.990,0.995)	0.004	0.996(0.995,0.996)
Mid	0.006	0.995(0.994,0.997)	0.004	0.997(0.996,0.998)
High	0.008	0.997(0.997,0.998)	0.005	0.998(0.998,0.998)
Posterior crown length (n=14)				
Low (RSM)	0.004	0.976(0.959,0.992)	0.004	0.979(0.967,0.991)
Mid	0.008	0.992(0.991,0.993)	0.006	0.992(0.988,0.996)
High	0.024	0.995(0.994,0.996)	0.016	0.996(0.995,0.997)

*Where the same feature provided the lowest (low), median (med) or the highest (high) values for both the upper and the lower arches, this has been indicated in brackets

4.3.3 Intra-method/rater results

The intra-method/rater SEMs ranged between 0.001 and 0.020 for the upper arch and between 0.001 and 0.022 for the lower arch. The percentage SEMs ranged between 0.010% and 0.325% for the upper arch and between 0.002% and 0.358% for the lower arch. The SEMs were on average were only one-third of inter-method values. All intra-method/rater ICCs ranged between 0.955 and 0.999 for the upper arch and between 0.971 and 0.999 for the lower arch. In the upper arch, the highest and the lowest ICCs were for the maximum and minimum arch widths of the lateral incisors respectively. For the lower arch, the highest ICCs were for the measurements of minimum arch widths of the first premolars and the lowest ICCs were for the crown lengths of the right second molars. The intra-method/rater data are reported in Supplementary Table 4.3. The supplementary tables are presented in the appendix at the end of this chapter.

4.3.4 Investigation of systematic differences

Inspection of Bland and Altman plots did not reveal any systematic patterns of difference. Less than 5% of all measurements were outside the limits of agreement. Regression of the differences or their absolute values on relevant covariates (crowding, rotation, presence of extra cusps, malocclusion, and erupting or partially impacted teeth) did not identify systematic influences.

4.4 Discussion

This study demonstrates that measurements of 110 landmark features of human dental casts made using an intra-oral 3D scanner are virtually indistinguishable from measurements of the same features made using conventional hand-held callipers (the standard method). The median difference of means for each category of feature was less than 0.06mm (less than 0.008% of the measurement) and the largest absolute value of difference was 0.134mm (0.196% of the measurement). There was no evidence of systematic differences between the measurements due to the presence of dental irregularities. However, there was a tendency for measurements made by the scanner to be slightly higher than those made using the callipers.

Measurement errors within 0.5mm are considered to be insignificant for therapeutic or restorative purposes (45). Because there are no standard guidelines for measurement errors that can be applied in forensic odontology, a threshold of 0.5mm was adopted as a reference point in this study. Based on this criterion, the measurement differences between the scanner and the calliper were trivial. The spread of measurements by each method for a single feature (the SEM) was generally less than one half of one percent, and the lowest ICC for any category of any category of feature was 0.904 with most ICCs in each category equal to at least 0.941. Measurements of the arch widths had the greatest correlations in both the upper and the lower arches. Of all measurements, the lowest correlations were for the posterior mesio-distal dimensions in the upper arches and the posterior bucco-lingual dimensions in the lower arches.

While the overall agreement between methods was excellent, in most cases the measurements made using the measuring tool provided with the Zfx IntraScan intra-oral 3D scanner were slightly larger than those made using the digital hand-held callipers. The slight differences between measurements made using the two methods may be due to the inability of the hand-held callipers to access extremities of spans of features and gaps. The measuring tool provided with the IntraScan intra-oral 3D scanner was capable of increasing the transparency of the virtual 3D dental casts to facilitate accurate placement of the measurement points. Based on that observation, it may be proposed that the measurements made by the scanner are more accurate for most categories of features. Because the process of making digital measurements is relatively new in comparison with the use of hand-held callipers, some initial training in the application of using the onscreen measuring tool may be required, but that preparation is not too onerous to preclude widespread use.

The design of this study and the analytical strategy used made it possible to concurrently assess inter-rater and intra-method/rater reliability. The inter-rater SEMs were one-half, and the intra-method/rater SEMs were one-third, of the inter-method values. The inter-rater and intra-method/rater ICCs were slightly higher than the excellent inter-method ICCs in consequence. These additional sources of error contribute to inter-method variation either directly or indirectly in combination with the method. It can be deduced that the excellent agreement between the measurements made by the scanner and those made by the calliper must be due not only to the technical accuracy of the scanner, but also to the limited scope it allows for variation between users of the equipment and between occasions of its use. Although slight variations were observed between measurements of specific categories of features, the correlations were excellent overall.

Previous studies by Al-Khatib et al (45), El-Zanaty et al (46), and Bootvong et al (47) have assessed the reliability of measurements of arch widths and tooth widths on dental casts and their corresponding virtual 3D models using digital callipers and 3D measuring software respectively. In this study, the highest correlation was for the arch-width measurements of upper and lower first premolars, and the lowest correlations were for the mesio-distal dimensions of the anterior teeth in both the upper and the lower arches. The features with highest correlations in this study were consistent with those from the three studies.

This is the first study to assess the reliability and validity of measurements made using a portable intra-oral 3D scanner for field use in forensics. By having two raters to measure and re-measure a total of 110 landmark dental features of both the upper and the lower arches, and comparing the results with the measurements using digital callipers, a thorough investigation of its reliability and validity was undertaken. The approach used allowed comprehensive assessment of inter-rater and inter-method/rater reliability and inter-method validity. Unlike previous studies, all 50 dental casts and the virtual 3D models were measured and re-measured by both methods and both raters. In this study, this was done with a sample size deemed sufficient to provide adequate statistical power for the analysis.

Nevertheless, this study has some limitations. There is a remote possibility of shared calibration error in the measurements by the scanner and callipers. Future studies are needed to compare other scanners and different measurement software. However, the size of the discoverable error in this study was so small that it does not preclude the use of the Zfx IntraScan intra-oral 3D scanner as a substitute for callipers. The dental irregularities found on the casts used in this study did not affect the results. Nevertheless, a study of dentitions with significant dental irregularities needs to be conducted to confirm this finding.

4.5 Significance and conclusion

This study demonstrates that the Zfx IntraScan intra-oral 3D scanner with its virtual on-screen measuring tool is a reliable and valid method for measuring the key features of virtual 3D dental casts. This technique has excellent potential for recording and accurately measuring dental features use in bite-mark analysis, and for research purposes.

4.6 References

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4.7 Appendix

Supplementary Table 4.1: Names of features and their abbreviations

URCI	Upper right central incisor
ULCI	Upper left central incisor
URLI	Upper right lateral incisor
ULLI	Upper left lateral incisor
URC	Upper right canine
ULC	Upper left canine
URFPM	Upper right first premolar
ULFPM	Upper left first premolar
URSPM	Upper right second premolar
ULSPM	Upper left second premolar
URFM	Upper right first molar
ULFM	Upper left first molar
URSM	Upper right second molar
ULSM	Upper left molar
LRCI	Lower right central incisor
LLCI	Lower left central incisor
LRLI	Lower right lateral incisor
LLLI	Lower left lateral incisor
LRC	Lower right canine
LLC	Lower left canine
LRFPM	Lower right first premolar
LLFPM	Lower left first premolar
LRSPM	Lower right second premolar
LLSPM	Lower left second premolar
LRFM	Lower right first molar
LLFM	Lower left first molar
LRSM	Lower right second molar
LLSM	Lower left molar
Max	Maximum arch width
Min	Minimum arch width
MDD	Mesio distal dimension
BLD	Bucco lingual dimension
CL	Crown length

Supplementary Table 4.2: Prevalence of dental irregularities that may influence reliability

Tooth	Dental irregularities				
	Crowding (%)	Rotations (%)	Extra cusp (%)	Malocclusion (%)	Partially erupted teeth (%)
URCI	8	10	0	0	0
ULCI	12	14	0	0	0
URLI	4	16	0	0	0
ULLI	6	12	0	0	0
URC	8	4	0	0	0
ULC	0	2	0	0	0
URFPM	0	4	0	0	0
ULFPM	0	0	0	0	0
URSPM	0	2	0	0	0
ULSPM	0	0	0	0	0
URFM	0	6	8	4	6
ULFM	0	2	0	2	4
URSM	0	0	2	0	4
ULSM	0	0	0	0	6
LRCI	12	4	0	0	0
LLCI	10	8	0	0	0
LRLI	6	8	0	0	0
LLLI	8	8	0	0	0
LRC	2	2	0	0	0
LLC	0	0	0	0	0
LRFPM	0	0	0	4	6
LLFPM	0	0	0	0	0
LRSPM	0	0	0	2	0
LLSPM	0	0	0	0	0
LRFM	0	0	2	0	6
LLFM	0	0	4	0	0
LRSM	0	0	0	0	8
LLSM	0	0	2	0	0

*Where the same feature provided the lowest (low), median (med) or the highest (high) values for both the upper and the lower arches, this has been indicated in brackets

Supplementary Table 4.3: Intra SEM and ICC for measurements made using the digital Zfx IntraScan intra-

oral 3D scanner

	Upper		Lower	
Category of feature*	SEM	ICC (95% CI)	SEM	ICC (95% CI)
Maximum arch width (n=13)				
Low	0.001	0.996(0.994,0.998)	0.001	0.997(0.995,0.998)
Mid	0.004	0.999(0.998,0.999)	0.004	0.997(0.996,0.998)
High	0.005	0.999(0.999,0.999)	0.011	0.998(0.997,0.999)
Minimum arch width (n=13)				
Low	0.001	0.955(0.898,0.998)	0.001	0.996(0.994,0.998)
Mid	0.004	0.999(0.998,1.000)	0.002	0.999(0.998,0.999)
High	0.017	0.999(0.999,0.999)	0.006	0.999(0.998,0.999)
Anterior bucco-lingual dimension (n=14)				
Low	0.002	0.985(0.978,0.993)	0.001	0.990(0.986,0.995)
Mid	0.004	0.996(0.993,1.000)	0.002	0.993(0.991,0.995)
High	0.010	0.998(0.997,0.998)	0.005	0.997(0.996,0.997)
Posterior bucco-lingual dimension (n=14)				
Low	0.001	0.980(0.976,0.985)	0.001	0.991(0.982,0.999)
Mid	0.003	0.992(0.989,0.994)	0.002	0.993(0.988,0.999)
High	0.006	0.998(0.998,0.999)	0.003	0.995(0.994,0.996)
Anterior mesio-distal dimension (n=14)				
Low	0.001	0.975(0.969,0.980)	0.001	0.985(0.981,0.989)
Mid	0.003	0.987(0.983,0.990)	0.001	0.991(0.988,0.993)
High	0.005	0.996(0.994,0.997)	0.002	0.996(0.995,0.997)
Posterior mesio-distal dimension (n=14)				
Low	0.001	0.974(0.970,0.978)	0.001	0.990(0.986,0.993)
Mid	0.003	0.990(0.986,0.994)	0.002	0.994(0.993,0.995)
High	0.006	0.996(0.994,0.997)	0.004	0.997(0.996,0.998)
Anterior crown length (n=14)				
Low (LCI)	0.001	0.992(0.989,0.995)	0.001	0.998(0.998,0.999)
Mid	0.003	0.997(0.996,0.998)	0.001	0.999(0.998,0.999)
High	0.008	0.998(0.997,0.999)	0.002	0.999(0.998,0.999)
Posterior crown length (n=14)				
Low (RSM)	0.003	0.980(0.964,0.996)	0.001	0.971(0.958,0.985)
Mid	0.008	0.992(0.987,0.998)	0.004	0.994(0.991,0.996)
High	0.020	0.997(0.997,0.998)	0.022	0.999(0.998,0.999)

*Where the same feature provided the lowest (low), median (med) or the highest (high) values for both the upper and the lower arches, this has been indicated in brackets

Supplementary Table 2.4: Definitions of categories of features

Category of feature	Definition
Maximum arch width between second molars	The maximum distance between the buccal convexity of the left second molar and on the buccal convexity of the right second molar
Minimum arch width between first molars	The minimum distance between the buccal convexity of the left first molar and on the buccal convexity of the right first molar
Maximum arch width between second pre-molars	The maximum distance between the buccal convexity of the left second pre-molar and on the buccal convexity of the right second pre-molar
Minimum arch width between first pre-molars	The minimum distance between the buccal convexity of the left first pre-molar and on the buccal convexity of the right first pre-molar
Maximum arch with between canines	The distance between the cusp tips of the anti-metric canines.
Maximum arch width between lateral incisors	The maximum distance between the most distal surface on the lateral incisors
Minimum arch width between lateral incisors	The minimum distance between the most mesial surface on the lateral incisors
Maximum arch width between central incisors	The maximum distance between the most distal surface on the central incisors
Minimum arch width between central incisors	The minimum distance between the most mesial surface on the central incisors
Crown length	The maximum distance between the incisal edge in anterior teeth and mesio-buccal cusp in the posterior teeth and the deepest point in the cemento-enamel junction.
Mesio-distal diameter	The maximum distance between the approximate point of contact of the adjacent crowns
Bucco-lingual diameter	The maximum distance between the labial or buccal surface and the lingual surface of tooth crowns

Chapter 5: Assessing the accuracy of matching 3D images of impressions of teeth with 3D images of candidate dog dental arches, with images made using the Zfx IntraScan intra-oral 3D scanner

Preface

Although the reliability and validity of the intra-oral 3D scanner was investigated in Chapter 4, the accuracy of matching 3D images of impressions of dog dentitions with 3D images of candidate dentitions had to be investigated. Chapter 5 investigates the accuracy of matching 3D images of candidate dog dental arches, using images made with the Zfx IntraScan intra-oral 3D scanner.

5.1 Introduction

The results of analysis of bite-marks left by the perpetrator have the potential to provide supporting evidence in criminal investigations. Because impressions of teeth made on pig skin have been shown to disappear within 30 minutes (2), it is critical to record them accurately and swiftly. Bite-marks are most commonly recorded using photographic methods although it is possible to create a three dimensional (3D) cast of the bite-mark using traditional casting techniques. Both these techniques have limitations, however. Photographic methods used to record bite-marks are prone to distortions (3), and standard casting techniques are invasive and may result in structural and chemical changes during the various stages of the casting procedure (4). This may lead to geometric inconsistencies between real teeth and their representations (5).

Images produced by 3D scanners have been used to record dentitions as an alternative to conventional dental casts for therapeutic use (6-9). A previous study has proposed that 3D imaging techniques have the potential to represent details better than conventional photographic techniques used in recording bite-marks (10). Although the use of 3D imaging tools in recording impressions of simulated bites has been demonstrated (11-13), the imaging tools used did not permit intra-oral scanning or were bulky and could not be transported to a crime scene. More recently the authors assessed the reliability and validity of measurements of landmark dental features of human dental cast that were made using a portable, non-invasive Zfx IntraScan intra-oral 3D scanner (1). The measurements made by different operators on different occasions were highly consistent and corresponded very closely to measurements of the same features made by digital hand-held callipers.

The purpose of this study was to assess the ability of the portable Zfx IntraScan intra-oral 3D scanner to record ideal impressions of dog dental arches made on modelling clay with sufficient accuracy to allow them to be matched to the dentition that caused them. The study provided us with the opportunity to identify key features or subsets of features that can be used to match impressions of teeth with dog dental arches.

5.2 Methods

5.2.1 Materials

For this study, 40 (23 upper and 17 lower) individual dental casts and skeletal jaws of dogs not restricted to any particular breed, sex or age were sourced from Advanced Animal Dentistry in Brisbane, Queensland, and three other Australian repositories: the Tasmanian Museum and Art Gallery in Hobart, the School of Zoology at the University of Tasmania in Hobart, and the Queen Victoria Museum and Art Gallery in Launceston. These jaws were from different dogs, and the dental casts were not fabricated from the skeletal jaws. There were 4 matching pairs of jaws, but for this study each jaw was considered to be an unrelated entity. Each dental cast and jaw were assigned separate identification numbers. To avoid distortions when making impressions, skeletal materials used in the study were selected only if the teeth were immobile. An additional upper jaw belonging to a dingo was sourced from the Queen Victoria Museum and Art Gallery and was used for cross-checking purposes. This study did not require a clearance from the ethics committee because the dental casts used in this study had been fabricated previously for therapeutic purposes.

5.2.2 Digital modelling

After an initial learning phase with the scanning device that was completed in under two weeks, two sets of virtual 3D images were made using a portable Zfx™ IntraScan intra-oral 3D scanner (Zfx™ IntraScan, Zfx GmbH, Dachau, Germany). Firstly, a virtual 3D model of each of the dog dental arches was made. Impressions for each dog jaw was then created by pressing the teeth of each dental arch against modelling clay. The impressions of dog dental arches were then scanned using the Zfx IntraScan intra-oral 3D scanner by applying the same scanning methodology to create a second set of 3D images. For the purpose of this study, virtual 3D images of dental casts or natural teeth are referred to as positive images, and virtual 3D images of the dental impressions (simulated bite marks) on clay are referred to as negative images. Figure 5.1a depicts a positive 3D image and Figure 5.1b depicts a negative 3D image. Figure 5.2a depicts 3D image of upper anterior dentition and 5.2b depicts 3D image of lower anterior dentition.This terminology is based on the definitions provided by Anusavice et al (14) for dental casts and dental impressions respectively. All scans were made at ambient room temperature. To standardise the scanning process, the scanner was calibrated before each scan.

The scanner was given a cooling period of 5-10 minutes between consecutive scanning of dental casts. A flat wooden slab was used to support the modelling clay from below. This was to avoid any inadvertent movement when creating the impression that may have resulted in distortion. The thickness of the impression material varied for each specimen because the dog dental arches used in this study were of different sizes. However, care was taken to ensure that the impression material covered all surfaces of the dental landmarks that were to be measured. The impressions were scanned immediately to avoid any distortions that may emerge over time due to drying or cracking of the clay. The resultant virtual 3D images were stored securely on University of Tasmania internal data drives in .stl file format with access restricted to the research team. The supporting software supplied with the scanner was used to view each virtual 3D model on a 17-inch LCD computer monitor with a screen resolution of 1366 x 768 pixels.

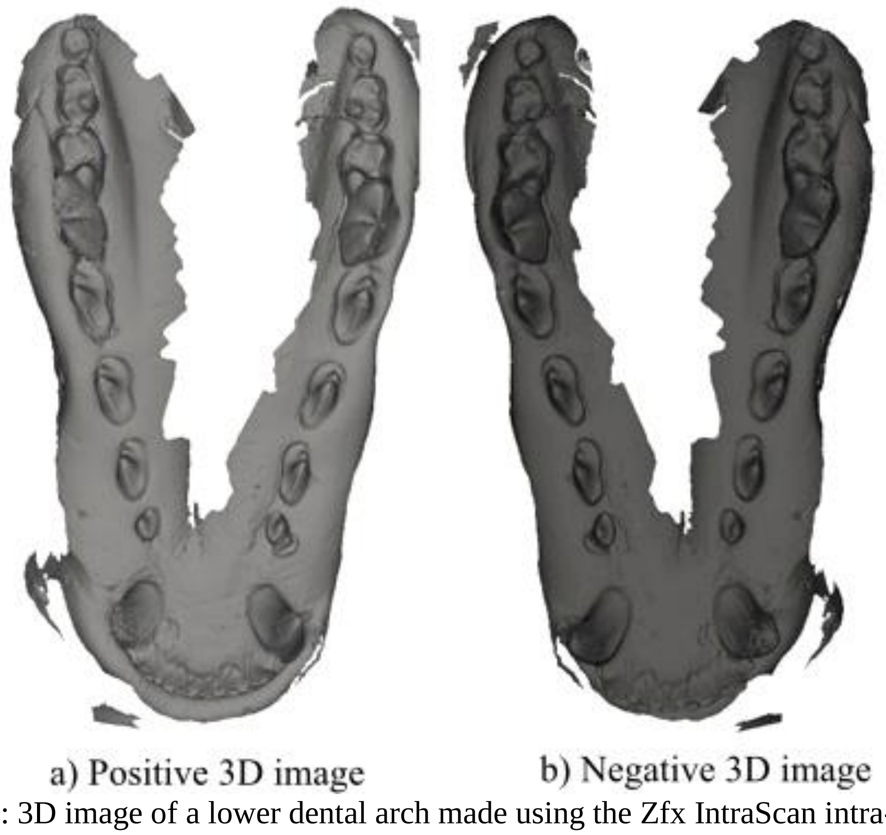

Figure 5.1: 3D image of a lower dental arch made using the Zfx IntraScan intra-oral 3D scanner

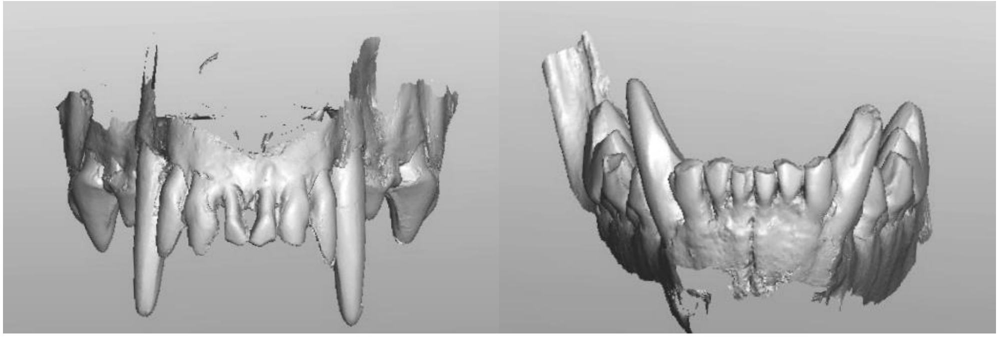

Figure 5.2 3D image of an upper and lower anterior dentition of a dog

5.2.3 Measurements

A single rater measured 79 landmark dental features on each of the upper and the lower dog dental arches using the virtual onscreen measuring tool that is part of the supporting software provided with the Zfx IntraScan intra-oral 3D scanner. The negative images of the impressions of the simulated bite marks produced by the scanner allowed measurements of the same features as those made on the positive images. Measurements were repeated at least one week later on both sets of virtual 3D images. For each pair of images, the formula used was:

The 79 measurement features included 20 crown lengths, 20 bucco-lingual measurements, 20 mesio-distal measurements and 19 inter-arch measurements for each specimen examined. These are standard dental measurements in human odontometry. They were used because there are no measurement definitions for dog dental arches that can be referenced for morphometric purposes. The existing definitions for measurements of dog dental features are limited to the functional regions of the teeth as outlined by Van Valkenburgh in 1989 (15). The arch width measurements were as defined by Foster et al 1969 (16), Lavelle et al 1970 (17) and Lavelle et al 1971 (18); mesio-distal measurements were consistent with the definitions of Barrett et al 1963 (19); bucco-lingual dimensions were consistent with the definitions provided by Barrett et al 1964 (20); crown length measurements were based on the definition of Bjorndal et al 1974 (21); and inter-canine widths were consistent with the definitions of Murmann et al 2006 (22). Abbreviations of the features measured in this study are listed in Supplementary Table 5.1.

5.2.4 Analytic approach

Repeated measurements of tooth crowns and arch widths were made using the virtual onscreen measuring tool applied to the virtual 3D images of the dentitions and the virtual 3D images of the impressions, and were assessed for consistency between raters and between the positive and negative images by: a) calculation of means of test-retest and positive-negative differences, b) inspection of Bland-Altman plots, c) regression of covariates that could influence measurement differences (crowding and rotation recorded as present or absent with respect to each tooth, and length of the jaw calculated as the distance from the point of contact of the central incisors to the mid-point of a straight line drawn from the distal surface of the second molars), d) calculation of standard error of measurement (SEM) expressed as a percentage of the average of the two sets of measurements, and e) calculation of intra-class correlation coefficients for consistency between measurements. The concurrent assessment of intra-rater reliability and inter-method validity was carried out using the approach of Eliasziw et al (23). The similarity between each set of measurements of a negative image and each set of measurements of a positive image was assessed by calculating the average of Euclidian distances of the measurements of the 79 landmark dental features on each negative 3D image from the measurements of those features on the positive 3D images. For each pair of images, the formula used was:

$$d(x_{i1}, x_{j2}) = \frac{\sum_{k=1}^{m_{ij}} \left(x_{i1k} - x_{j2k} \right)^2}{m_{ij}}$$

where $x_{i1}\,(i = 1, 2, \ldots 40)$ denotes each negative image and $x_{i1k}\,(k = 1, 2, \ldots 79)$ the measurements of its 79 features, $x_{j2}\,(j = 1, 2, \ldots 40)$ denotes each positive image and $x_{j2k}\,(k = 1, 2, \ldots 79)$ the measurements of its 79 features, and m_{ij} is the number of features of negative image $i\,(i = 1, 2, \ldots 40)$ for which measurements were available also from the positive image $j\,(j = 1, 2, \ldots 40)$ with maximum $m_{ij} = 79$. Because the sizes of the jaws and dental arches used in this study varied widely, the measurements were scaled to standardise the inter-canine distances. The measurements of the inter-canine distances were selected for standardisation because they are considered to be key components in forensic investigations of bite-marks (24). Error rates associated with matching measurements of 79 landmark features made on positive 3D images with those made on the negative 3D images after scaling the inter-canine distances were estimated as percentage of disagreement.

5.3 Results

Characteristics of the study sample are reported in Table 5.1. In the sample, 10% of the dogs had a complete set of teeth. Most (37/40) dentitions were at least 90% complete with at most 10% of the teeth missing. The remaining 7.5% (3/40) of dental arches were less complete with a maximum of 40% of the teeth missing. The missing measurements comprised less than 15% of the total number of measurements of 40 complete dentitions. In the anterior biting dentition, the first incisors were absent in 20% of the jaws, the second incisors were absent in 18% of the jaws, the third incisors were absent in 15% of the jaws and the canines were absent of 7.5% of the jaws. The highest prevalence of crowding was in the right first incisors in the upper arch and the left first incisor in the lower arch. The greatest prevalence of rotations was in the right and left first incisors in the upper arch and the left first incisors in the lower arch.

Table 5.1: Prevalence of dental irregularities that may influence reliability

ID	Length of jaw*	Completeness	Crowding†	Rotation†
DC001	Medium	68.35%	5%	0
DC002	Short	58.22%	0	0
DC003	Medium	98.73%	0	0
DC004	Long	93.67%	0	0
DC005	Long	74.68%	0	0
DC006	Long	62.02%	0	0
DC007	Short	88.60%	5%	0
DC008	Medium	87.34%	0	0
DC009	Medium	72.15%	0	5%
DC010	Long	69.62%	0	0
DC011	Medium	81.01%	0	0
DC012	Long	62.02%	0	0
DC013	Short	63.16%	0	0
DC014	Medium	100%	0	5%
DC015	Long	58.22%	0	0
DC016	Medium	93.67%	0	0
DC017	Short	63.29%	0	0
DC018	Medium	59.49%	0	0
DC019	Medium	92.40%	0	0
DC020	Long	98.73%	0	0
DC021	Long	92.40%	0	0
DC022	Medium	86.07%	0	0
DC023	Long	92.40%	0	0
DC024	Medium	88.60%	0	0
DC025	Medium	88.60%	0	0
DC026	Medium	96.20%	0	0
DC027	Long	98.73%	0	0
DC028	Long	98.73%	0	0
DC029	Medium	89.87%	0	0

DC030	Long	93.67%	0	0
DC031	Short	100%	0	0
DC032	Short	83.54%	0	0
DC033	Medium	88.60%	0	0
DC034	Long	64.62%	0	0
DC035	Long	79.74%	0	0
DC036	Medium	75.94%	5%	0
DC037	Medium	98.73%	0	0
DC038	Medium	100%	0	0
DC039	Long	100%	0	0
DC040	Long	73.41%	0	0

*Jaw length greater than 90mm=log, jaw length greater than 70mm=medium, jaw length less than70mm=short
†Calculated as the percentage of teeth affected by crowding and rotation

Means of measurements for the 79 landmark features made from the positive and negative images of dental arches using the measuring tool provided with the Zfx IntraScan intra-oral 3D scanner are reported in Supplementary Table 5.2. Difference of means of measurements for the 79 landmark features made from the positive and negative images of dog dental arches are reported in Table 5.2. The measurements made from the negative images were generally higher than those made from the positive images. The negative measurements were greater on average for 57/79 of the features in the upper arch and for 71/79 of the features in the lower arch.

Table5.2: Difference of means of measurements made on for positive and negative 3D images of dog dental arches using a Zfx Intrascan intra-oral 3D scanner

Category of feature†	Upper	Lower
	Diff of means* (SD) (mm)	Diff of means* (SD) (mm)
Maximum arch width (n=11)		
Low	-0.046(0.032)	-0.024 (0.017)
Mid (UC)	-0.017(0.012)	-0.007 (0.005)
High	0.002(0.002)	0.037 (0.026)
Minimum arch width (n=8)		
Low	-0.020(0.014)	-0.017 (0.012)
Mid	-0.013(0.009)	-0.001 (0.008)
High	0.014(0.009)	0.003 (0.011)
Anterior bucco-lingual dimension (n=8)		
Low	-0.033(0.023)	-0.036 (0.025)
Mid	-0.018(0.013)	-0.013 (0.009)
High	0.020(0.014)	-0.009 (0.006)
Posterior bucco-lingual dimension (n=12)		
Low	-0.028(0.020)	-0.038 (0.027)
Mid	-0.009(0.006)	-0.008 (0.006)
High (LTPM)	0.033(0.023)	0.003 (0.002)
Anterior mesio-distal dimension (n=8)		
Low	-0.024(0.017)	-0.025 (0.017)
Mid	-0.015(0.010)	-0.013 (0.009)
High	0.026(0.018)	-0.003 (0.002)
Posterior mesio-distal dimension (n=12)		
Low	-0.028(0.019)	-0.036 (0.025)
Mid	-0.001(0.012)	-0.018 (0.013)
High	0.019(0.014)	0.019 (0.013)
Anterior crown length (n=8)		
Low	-0.022(0.016)	-0.034 (0.024)
Mid (RSI)	-0.008(0.005)	-0.023 (0.016)
High	0.010(0.007)	-0.006 (0.004)
Posterior crown length (n=12)		
Low	-0.016(0.011)	-0.041 (0.029)
Mid	-0.001(0.001)	-0.017 (0.012)
High (LFPM)	0.011(0.008)	0.018 (0.012)

*Calculated as the average of the differences of negative measurements from positive measurements

†Where the same feature provided the lowest (low), median (med) or the highest (high) values for both the upper and the lower arches, this has been indicated in brackets

5.3.1 Intra-rater results

The intra-rater SEMs ranged between 0.041 and 0.076 for the upper arch, and between 0.043 and 0.073 for the lower arch. As a percentage of the average of the measurements for the positive images, the percentage SEM ranged between 0.050% and 1.450% for the upper arch and 0.021% and 1.609% for the lower arch. For the negative images, the SEMs ranged between 0.022% and 1.508% for the upper arch and 0.066% and 1.553% for the lower arch. All intra-rater ICCs were greater than 0.939 for both the upper and the lower arches. The intra-rater results are reported in Supplementary Table 5.3.

5.3.2 "Inter-method" results

To allow evaluation of the measurement differences in the same metrics of SEMs and ICCs, the measurements of the positive and negative images are compared in Supplementary Table 5.4 as if they are the results of different methods of measuring the same features. The "inter-method" SEMs ranged between 0.043 and 0.078 in the upper arch and 0.045 and 0.074 in the lower arch. As a percentage of the average of the measurements, the percentage SEMs ranged between 0.078% and 1.485% for the upper arch and 0.105% and 1.634% for the lower arch. All "inter-method" ICCs were greater than 0.972 for both the upper and the lower arches.

5.3.3 Investigation of systematic patterns

Inspection of Bland-Altman plots did not reveal any systematic patterns of difference. Less than 4% of all measurements were outside the 95% limits of agreement. Regression of differences of absolute values on relevant covariates such as crowding and rotation did not identify systematic influences.

5.3.4 Error rates

Mean distances between the positive and negative images of each dentition, and percentages of matches for subsets of features, are reported in Table 5.3. There was a 100% percent match with 0% error rate for matching all available features (maximum 79) of each negative image to a positive image. To assess the effect of individual features or subsets of features on the match rates, some features were removed and the matching process was repeated. On matching only the arch widths of the anterior teeth, the accuracy of the matches dropped to 5.4%. On matching measurements of only the arch widths of the first and the second incisors with inter-canine widths, the accuracy increased slightly to 8.1%. There was an accuracy of 53.3% when only the arch widths of the first central incisors were matched. On matching only the arch widths and the inter-canine distances, the accuracy of the matches increased to 89.2%. On matching all features of teeth most commonly responsible for bite-marks (anterior dentition)**,** there was a 100% match. On matching only the inter-canine distances without scaling, the images matched 31 times out of 37 times with a match rate of 83.8%. For additional testing, measurements from one of the 23 upper jaws used in this study were replaced with measurements made on a 3D model of an upper jaw of a dingo. On matching measurements from all available features, the accuracy dropped to 97.67% from 100% as expected because there was no impression of that dentition. All other subsets of features matched with 100% accuracy.

Table 5.3: Means of Euclidian distances and percentages of matches of negative images of impressions to positive images of dentitions

Subset of features matched	Average distance (mm)	Matched
	mean (SD)	% (n/N)
All features	19.31(24.11)	100%(37/37)
All features except mesio-distal dimensions	21.94(30.82)	100%(37/37)
All features except bucco-lingual dimensions	24.43(31.42)	100%(37/37)
All features except crown lengths	22.40(32.03)	100%(37/37)
All features except arch widths	9.05(06.56)	100%(37/37)
All features except inter-canine widths	19.69(24.60)	100%(37/37)
All features except maximum arch widths	15.65(20.11)	100%(37/37)
All features except minimum arch widths	14.01(11.91)	100%(37/37)
Only mesio-distal dimensions	11.83(10.12)	100%(37/37)
Only mesio-distal dimensions with arch widths	31.97(47.58)	100%(37/37)
Only bucco-lingual dimensions	4.85(04.67)	100%(37/37)
Only bucco-lingual dimensions with arch widths	28.20(47.28)	100%(37/37)
Only crown lengths	10.12(08.47)	100%(37/37)
Only crown lengths with arch widths	31.40(46.13)	100%(37/37)
Only maximum arch width without inter-canine widths	53.93(76.49)	100%(37/37)
Only minimum arch widths without inter-canine widths	77.22(182.22)	100%(37/37)
Only arch widths of anterior teeth	28.23(69.57)	5.4%(02/37)
Only arch widths of anterior teeth without third central incisor	11.67(27.27)	8.1%(03/37)
Only arch widths of first central incisors	4.69(07.66)	53.33%(16/30)
Only arch widths with inter-canine widths	56.86(101.00)	89.18%(33/37)
Only anterior dentition	11.26(16.57)	100%(37/37)

5.4 Discussion

This study confirmed that the measurements of 79 landmark dental features made from negative images of undistorted impressions of dog dental arches in clay were nearly identical to those made from the positive images of the dog dental arches. The largest average absolute value of difference between the measurements was 0.007% in the upper arch and 0.001% in the lower arch. In intra-rater comparisons, the ICCs ranged between 0.977 and 0.999. The lowest ICCs were for the bucco-lingual dimensions of the left third premolars in the upper arch and the maxillary arch widths of the last premolars in the lower arch. Between measurements of positive and negative images, the ICCs were excellent with the lowest ICC for any category of feature being 0.937 and with most ICC's in each category greater than 0.990. In comparisons of positive and negative images, the lowest ICCs were for the bucco-lingual dimensions of the right first premolars in the upper arch and the minimum arch widths of the first central incisors. There was a tendency for measurements made on the negative images to be slightly greater than those made on the positive images. This may be due to the displacement of the impression material due to contact with teeth. This displacement of skin will have to be considered when examining actual bite-marks on skin (25). In this study, the differences in measurements were so small that it was possible to match negative images to images of dentitions with 100% accuracy.

The portable Zfx IntraScan intra-oral 3D scanner has been assessed previously by the authors of this paper (1) for its ability to reliably and accurately record landmark dental features of human dentitions. The measuring tool provided with the 3D scanner produced measurements of landmark human dental features as reliably and accurately as conventional handheld callipers. The measurements of key features of dog dental arches made using the instrument are highly reliable and, to the extent that the "inter-method" results attest to validity, are highly accurate as well.

The National Academy of Science report published in 2009 (26) indicated that to establish the scientific credibility of bite-mark analysis, it was important to investigate whether particular numbers and types of features are required to establish a match between bite-marks and the suspect dentitions. In this study, impressions of teeth of dogs to their dentitions could be matched accurately but, in analysis of subsets of key features from the 79 features that were measured, some features contributed to the overall match rate more than the other features. When matching all 79 features of the positive images with those of the negative 3D images, there was 100% accuracy in the matches. The accuracy decreased significantly when only the measurements of arch-widths of the anterior dentition were matched. The results suggest that inter-canine widths are key components in bite-mark analysis, and this finding is consistent with those from a previous study (27). As indicated by Bernitz et al (28), inter-canine widths can be of great value in eliminating dogs as suspected perpetrators. These results demonstrate that it is possible to establish a 100% match by measuring landmark dental features of the anterior dentition commonly responsible for bite-marks (24, 29). On substituting measurements from one of the upper jaws with measurements made from a 3D model of a dingo jaw, the match rates dropped as expected.

This study has several strengths. It provides the first assessments of the reliability of measurements made on 3D images of dental arches using a portable, non-invasive intra-oral 3D scanner. Also for the first time matching measurements made on positive and negative 3D images of dog dental arches were compared and error rates associated with matching was calculated. The attempt to identify a subset of best features that need to be matched during forensic investigations of dog-bites was a third novel contribution.

The main limitation of this study is that the impressions used in this study were made without distortion, and that limits the findings to impressions of teeth that are of exceptional representational quality. Another limitation was the large inter-dog variation in jaw size and shape in this relatively small sample of dog dental arches. The accuracy of matching reported in this study may be lower in real world applications because there is likely to be less variation between the dentitions of similarly-sized dogs of the same breed than between those of the dogs in this sample. To minimise this variation by scaling the measurements so that each set had the same inter-canine distance was attempted, but cannot claim that this resolved the problem completely. In addition, missing teeth provided a challenge and require a qualification on the interpretation of results. On the one hand, the error rates may have been incorrectly estimated because measurements for all features were not available. On the other hand, in real life forensic investigations of bite-marks, missing teeth may be of great value in excluding suspects with a more or less complete dentition. The absence of the indentation of a tooth in a bite-mark may mean that the tooth is missing. Alternatively, it may also mean that the tooth is mal-aligned, or partially erupted or it may have been obstructed due to clothing. This provides useful information that can be used in matching bite-marks to suspect dentitions. Finally, the dental casts used in this study belonged to a diseased sub-population of dogs that required some form of dental intervention. They may not be representative of a healthy population without dental problems.

5.5 Significance and conclusion

In conclusion, this study demonstrates that the portable Zfx IntraScan intra-oral 3D scanner enables measurements of the undistorted impressions of dental features in modelling clay with sufficient accuracy to allow identification of the dentition responsible. In principle, use of the scanner makes it feasible to estimate error rates in matching 3D images of dentitions to 3D images of their impressions. The demonstration of this was undertaken in ideal circumstances in which impressions of all available teeth were made without distortions. Importantly, the results of this proof-of-concept study suggest that the matching can be accomplished without need for subjective inputs by human operators, but this requires further experimental verification. It also requires confirmation in real world cases. Further research is required to gain a better understanding of how this technology might assist to overcome the complexities associated with bite-mark analysis. For example, the value of the tool could be extended by using it to create repositories of 3D images of human and animal dentitions that may be consulted during forensic investigations of bite-marks.

5.6 References

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5.7 Appendix

Supplementary Table 3.1 Names of features and their abbreviation

Feature	Abbreviation
Right First Incisor	RFI
Left First Incisor	LFI
Right Second Incisor	RSI
Left Second Incisor	LSI
Right Third Incisor	RTI
Left Third Incisor	LTI
Right Canine	RC
Left Canine	LC
Right First Pre Molar	RFPM
Left First Pre Molar	LFPM
Right Second Pre Molar	RSPM
Left Second Pre Molar	LSPM
Right Third Pre Molar	RTPM
Left Third Pre Molar	LTPM
Right Last Pre Molar	RLPM
Left Last Pre Molar	LLPM
Right First Molar	RFM
Left First Molar	LFM
Right Second Molar	RSM
Left Second Molar	LSM
First Central Incisor	FCI
Second Central Incisor	SCI
Third Central Incisor	TCI
Canine	UC
First Pre Molar	FPM
Second Pre Molar	SPM
Third Pre Molar	TPM
Last Pre Molar	LPM
First Molar	FM
Second Molar	SM
Maximum Arch Width	Max
Minimum Arch Width	Min
Mesio-Distal Dimension	MDD
Bucco-Lingual Dimension	BLD

Supplementary Table 5.2: Means of measurements (mm) of landmark dental features made using the Zfx IntraScan intra-oral 3D scanner

Feature	Upper				Lower			
	Positive		Negative		Positive		Negative	
	Mean (SD)		Mean (SD)		Mean (SD)		Mean (SD)	
Right First Incisor MDD	4.792	(0.060)	4.766	(0.005)	3.394	(0.022)	3.418	(0.045)
Right First Incisor BLD	4.967	(0.025)	4.960	(0.007)	4.047	(0.018)	4.068	(0.028)
Right First Incisor CL	6.328	(0.020)	6.340	(0.009)	4.581	(0.025)	4.608	(0.021)
Left First Incisor MDD	4.844	(0.035)	4.853	(0.020)	3.637	(0.027)	3.650	(0.016)
Left First Incisor BLD	5.045	(0.026)	5.074	(0.040)	4.056	(0.031)	4.081	(0.050)
Left First Incisor CL	5.940	(0.021)	5.930	(0.017)	4.539	(0.022)	4.572	(0.050)
Right Second Incisor MDD	5.420	(0.027)	5.444	(0.025)	4.476	(0.008)	4.486	(0.011)
Right Second Incisor BLD	5.496	(0.029)	5.515	(0.012)	4.996	(0.040)	4.996	(0.032)
Right Second Incisor CL	7.379	(0.026)	7.387	(0.007)	5.440	(0.016)	5.463	(0.038)
Left Second Incisor MDD	5.561	(0.013)	5.583	(0.014)	4.518	(0.020)	4.533	(0.030)
Left Second Incisor BLD	5.719	(0.033)	5.749	(0.031)	4.945	(0.020)	4.979	(0.035)
Left Second Incisor CL	7.284	(0.032)	7.298	(0.043)	5.300	(0.019)	5.334	(0.035)
Right Third Incisor MDD	7.106	(0.027)	7.127	(0.017)	5.865	(0.036)	5.869	(0.011)
Right Third Incisor BLD	6.490	(0.038)	6.470	(0.010)	5.439	(0.038)	5.452	(0.052)
Right Third Incisor CL	9.802	(0.015)	9.825	(0.022)	6.962	(0.023)	6.983	(0.007)
Left Third Incisor MDD	7.117	(0.019)	7.132	(0.005)	5.936	(0.019)	5.961	(0.020)
Left Third Incisor BLD	6.437	(0.006)	6.470	(0.030)	5.461	(0.031)	5.479	(0.037)
Left Third Incisor CL	9.442	(0.029)	9.440	(0.005)	6.899	(0.033)	6.906	(0.022)
Right Canine MDD	10.642	(0.026)	10.647	(0.020)	11.531	(0.024)	11.549	(0.016)
Right Canine BLD	6.769	(0.033)	6.777	(0.034)	8.009	(0.014)	8.045	(0.035)
Right Canine CL	17.233	(0.044)	17.239	(0.024)	16.148	(0.020)	16.168	(0.007)
Left Canine MDD	10.389	(0.014)	10.312	(0.054)	11.351	(0.014)	11.371	(0.022)
Left Canine BLD	6.610	(0.015)	6.635	(0.014)	7.825	(0.026)	7.835	(0.020)
Left Canine CL	17.243	(0.034)	17.263	(0.027)	16.113	(0.019)	16.133	(0.028)
Right First Pre Molar MDD	5.706	(0.074)	5.689	(0.018)	4.833	(0.027)	4.856	(0.019)
Right First Pre Molar BLD	3.763	(0.019)	3.774	(0.009)	3.326	(0.047)	3.338	(0.031)
Right First Pre Molar CL	4.036	(0.022)	4.042	(0.021)	3.408	(0.026)	3.440	(0.023)
Left First Pre Molar MDD	5.762	(0.042)	5.778	(0.013)	4.825	(0.028)	4.838	(0.008)
Left First Pre Molar BLD	4.036	(0.033)	4.058	(0.014)	3.449	(0.047)	3.458	(0.024)
Left First Pre Molar CL	4.091	(0.040)	4.080	(0.023)	3.323	(0.040)	3.305	(0.014)
Right Second Pre Molar MDD	10.232	(0.038)	10.212	(0.007)	9.525	(0.039)	9.544	(0.032)
Right Second Pre Molar BLD	4.037	(0.029)	4.042	(0.003)	4.544	(0.038)	4.562	(0.025)
Right Second Pre Molar CL	4.923	(0.029)	4.926	(0.023)	5.225	(0.023)	5.266	(0.043)
Left Second Pre Molar MDD	10.255	(0.046)	10.259	(0.016)	9.304	(0.034)	9.305	(0.003)
Left Second Pre Molar BLD	4.274	(0.001)	4.303	(0.023)	4.434	(0.010)	4.460	(0.022)
Left Second Pre Molar CL	4.938	(0.022)	4.930	(0.005)	5.227	(0.037)	5.252	(0.036)
Right Third Pre Molar MDD	11.489	(0.019)	11.487	(0.014)	10.640	(0.019)	10.642	(0.024)
Right Third Pre Molar BLD	4.746	(0.041)	4.754	(0.020)	5.306	(0.009)	5.308	(0.018)
Right Third Pre Molar CL	5.282	(0.048)	5.274	(0.014)	5.642	(0.050)	5.667	(0.032)
Left Third Pre Molar MDD	11.497	(0.024)	11.522	(0.020)	10.660	(0.043)	10.656	(0.005)

Left Third Pre Molar BLD	4.932	(0.034)	4.879	(0.053)	5.132	(0.052)	5.129	(0.015)
Left Third Pre Molar CL	5.334	(0.037)	5.332	(0.019)	5.778	(0.030)	5.787	(0.000)
Right Last Pre Molar MDD	18.180	(0.040)	18.177	(0.008)	12.183	(0.040)	12.217	(0.024)
Right Last Pre Molar BLD	7.580	(0.046)	7.583	(0.034)	6.359	(0.035)	6.390	(0.037)
Right Last Pre Molar CL	10.194	(0.054)	10.208	(0.041)	6.842	(0.042)	6.854	(0.047)
Left Last Pre Molar MDD	18.220	(0.034)	18.221	(0.021)	11.985	(0.013)	12.019	(0.030)
Left Last Pre Molar BLD	7.628	(0.044)	7.639	(0.032)	6.300	(0.028)	6.321	(0.024)
Left Last Pre Molar CL	9.464	(0.033)	9.479	(0.026)	6.586	(0.015)	6.620	(0.014)
Right First Molar MDD	13.726	(0.047)	13.725	(0.019)	18.670	(0.024)	18.707	(0.020)
Right First Molar BLD	13.428	(0.019)	13.447	(0.020)	8.641	(0.032)	8.658	(0.013)
Right First Molar CL	7.188	(0.022)	7.204	(0.012)	9.831	(0.035)	9.849	(0.030)
Left First Molar MDD	13.211	(0.019)	13.225	(0.014)	18.602	(0.038)	18.618	(0.026)
Left First Molar BLD	13.783	(0.032)	13.784	(0.000)	8.102	(0.031)	8.409	(0.404)
Left First Molar CL	6.969	(0.037)	6.969	(0.005)	10.567	(0.004)	10.599	(0.041)
Right Second Molar MDD	9.474	(0.035)	9.474	(0.022)	9.687	(0.037)	9.698	(0.016)
Right Second Molar BLS	9.824	(0.031)	9.833	(0.025)	6.624	(0.046)	6.622	(0.004)
Right Second Molar CL	4.907	(0.037)	4.908	(0.027)	5.799	(0.044)	5.808	(0.016)
Left Second Molar MDD	9.905	(0.032)	9.933	(0.015)	9.575	(0.050)	9.556	(0.001)
Left Second Molar BLD	9.792	(0.040)	9.812	(0.015)	6.713	(0.025)	6.705	(0.017)
Left Second Molar CL	4.654	(0.051)	4.649	(0.031)	6.313	(0.028)	6.315	(0.028)
First Central Incisor Max	10.211	(0.011)	10.231	(0.038)	7.235	(0.026)	7.240	(0.004)
First Central Incisor Min	3.060	(0.052)	3.063	(0.040)	1.005	(0.030)	1.016	(0.027)
Second Central Incisor Max	20.958	(0.045)	20.955	(0.021)	15.988	(0.029)	15.994	(0.003)
Second Central Incisor Min	10.742	(0.021)	10.762	(0.021)	10.744	(0.035)	10.741	(0.015)
Third Central Incisor Max	28.270	(0.040)	28.269	(0.014)	24.017	(0.052)	24.030	(0.033)
Third Central Incisor Min	22.240	(0.033)	22.261	(0.028)	19.616	(0.028)	19.633	(0.029)
Canine Max	39.395	(0.034)	39.453	(0.045)	35.059	(0.034)	35.067	(0.004)
First Pre Molar Max	36.035	(0.020)	36.046	(0.002)	26.268	(0.033)	26.292	(0.006)
First Pre Molar Min	29.163	(0.044)	29.172	(0.037)	19.985	(0.048)	19.985	(0.028)
Second Pre Molar Max	39.952	(0.028)	39.978	(0.027)	31.326	(0.040)	31.345	(0.033)
Second Pre Molar min	31.382	(0.019)	31.400	(0.011)	23.916	(0.032)	23.931	(0.025)
Third Pre Molar Max	46.353	(0.035)	46.363	(0.031)	39.429	(0.043)	39.445	(0.022)
Third Pre Molar Min	34.066	(0.032)	34.052	(0.007)	30.507	(0.052)	30.508	(0.008)
Last Pre Molar Max	62.243	(0.016)	62.263	(0.021)	47.019	(0.023)	46.982	(0.018)
Last Pre Molar Min	42.951	(0.038)	42.965	(0.017)	35.811	(0.005)	35.815	(0.026)
First Molar Max	63.252	(0.004)	63.298	(0.014)	52.609	(0.022)	52.618	(0.015)
First Molar Min	35.901	(0.025)	35.899	(0.009)	37.439	(0.036)	37.443	(0.011)
Second Molar Max	57.130	(0.024)	57.150	(0.025)	53.601	(0.029)	53.610	(0.012)
Second Molar Min	36.759	(0.015)	36.775	(0.014)	40.948	(0.007)	40.973	(0.015)

Supplementary Table 5.3: Intra-rater SEM (mm) and ICC for measurements made using the Zfx IntraScan intra-oral 3D scanner

	Upper			Lower		
Category of feature*	SEM	ICC	(95% CI)	SEM	ICC	(95% CI)
Maximum arch width (n=11)						
Low	0.047	0.997	(0.992,0.999)	0.046	0.979	(0.942,0.993)
Mid	0.053	0.998	(0.996,0.999)	0.051	0.998	(0.995,0.999)
High (FM)	0.064	0.999	(0.999,0.999)	0.057	0.999	(0.999,0.999)
Minimum arch width (n=8)						
Low (FCI)	0.041	0.988	(0.825,0.999)	0.048	0.988	(0.947,0.997)
Mid	0.052	0.999	(0.997,0.999)	0.051	0.999	(0.999,0.999)
High	0.078	0.999	(0.999,0.999)	0.061	0.999	(0.999,0.999)
Anterior bucco-lingual dimension (n=8)						
Low	0.048	0.986	(0.967,0.994)	0.052	0.995	(0.988,0.998)
Mid	0.055	0.995	(0.986,0.998)	0.056	0.997	(0.994,0.999)
High (RC)	0.067	0.997	(0.993,0.998)	0.063	0.999	(0.997,0.999)
Posterior bucco-lingual dimension (n=12)						
Low	0.048	0.939	(0.853,0.974)	0.043	0.989	(0.970,0.996)
Mid	0.054	0.996	(0.991,0.998)	0.054	0.996	(0.989,0.998)
High	0.068	0.999	(0.999,0.999)	0.061	0.999	(0.998,0.999)
Anterior mesio-distal dimension (n=8)						
Low (RFI)	0.048	0.982	(0.953,0.993)	0.044	0.991	(0.976,0.997)
Mid	0.056	0.997	(0.993,0.999)	0.054	0.997	(0.994,0.999)
High (RC)	0.061	0.998	(0.996,0.999)	0.073	0.998	(0.997,0.999)
Posterior mesio-distal dimension (n=12)						
Low	0.047	0.977	(0.939,0.991)	0.046	0.997	(0.992,0.999)
Mid	0.058	0.998	(0.996,0.999)	0.054	0.998	(0.996,0.999)
High	0.076	0.999	(0.999,0.999)	0.060	0.999	(0.999,0.999)
Anterior crown length (n=8)						
Low	0.049	0.998	(0.995,0.999)	0.049	0.998	(0.996,0.999)
Mid (LSI)	0.059	0.998	(0.996,0.999)	0.056	0.999	(0.998,0.999)
High (LC)	0.067	0.999	(0.999,0.999)	0.068	0.999	(0.999,0.999)
Posterior crown length (n=12)						
Low	0.049	0.996	(0.991,0.998)	0.046	0.995	(0.987,0.998)
Mid	0.060	0.998	(0.996,0.999)	0.058	0.998	(0.994,0.999)
High	0.071	0.999	(0.997,0.999)	0.064	0.999	(0.999,0.999)

* Where the same feature provided the lowest (low), median (med) or the highest (high) values for both the upper and the lower arches, this has been indicated in brackets

Supplementary Table 5.4: SEM (mm) and ICC for measurements of positive and negative images made using the Zfx IntraScan intra-oral 3D scanner

	Upper			Lower		
Category of feature*	SEM	ICC	(95% CI)	SEM	ICC	(95% CI)
Maximum arch width (n=11)						
Low	0.048	0.997	(0.994,0.999)	0.048	0.989	(0.957,0.992)
Mid	0.053	0.998	(0.997,0.999)	0.055	0.997	(0.994,0.999)
High (FCI)	0.061	0.999	(0.999,0.999)	0.070	0.999	(0.999,0.999)
Minimum arch width (n=8)						
Low (FM)	0.043	0.988	(0.958,0.999)	0.048	0.988	(0.976,0.998)
Mid	0.055	0.999	(0.997,0.999)	0.052	0.999	(0.999,0.999)
High	0.078	0.999	(0.999,0.999)	0.061	0.999	(0.999,0.999)
Anterior bucco-lingual dimension (n=8)						
Low	0.049	0.984	(0.970,0.993)	0.052	0.995	(0.993,0.998)
Mid	0.057	0.996	(0.993,0.998)	0.059	0.998	(0.997,0.999)
High (RFI)	0.072	0.997	(0.994,0.999)	0.067	0.999	(0.998,0.999)
Posterior bucco-lingual dimension (n=12)						
Low	0.048	0.972	(0.944,0.989)	0.045	0.989	(0.985,0.997)
Mid	0.059	0.989	(0.977,0.995)	0.055	0.996	(0.993,0.998)
High	0.068	0.999	(0.999,0.999)	0.061	0.999	(0.999,0.999)
Anterior mesio-distal dimension (n=8)						
Low (RFI)	0.050	0.980	(0.960,0.992)	0.046	0.991	(0.984,0.997)
Mid	0.059	0.997	(0.994,0.998)	0.055	0.997	(0.995,0.999)
High	0.066	0.998	(0.997,0.999)	0.074	0.998	(0.997,0.999)
Posterior mesio-distal dimension (n=12)						
Low	0.050	0.977	(0.955,0.991)	0.046	0.997	(0.995,0.999)
Mid	0.062	0.998	(0.997,0.999)	0.056	0.998	(0.997,0.999)
High	0.076	0.999	(0.999,0.999)	0.063	0.999	(0.999,0.999)
Anterior crown length (n=8)						
Low	0.049	0.998	(0.996,0.999)	0.050	0.998	(0.997,0.999)
Mid (LSI)	0.062	0.999	(0.998,0.999)	0.056	0.999	(0.998,0.999)
High	0.071	0.999	(0.999,0.999)	0.072	0.999	(0.999,0.999)
Posterior crown length (n=12)						
Low	0.049	0.996	(0.995,0.998)	0.047	0.994	(0.985,0.998)
Mid	0.060	0.998	(0.996,0.999)	0.059	0.998	(0.997,0.999)
High	0.071	0.999	(0.998,0.999)	0.067	0.999	(0.999,0.999)

* Where the same feature provided the lowest (low), median (med) or the highest (high) values for both the upper and the lower arches, this has been indicated in brackets

Chapter 6: Summary and conclusion

6.1 Background

Forensic investigation of bite-marks on humans has the potential to provide evidence that can be used to identify the perpetrator of a bite. Bite-mark evidence has been used in legal proceedings since 1692 but, recently, bite-mark analysis has been subject to substantial criticism. In the USA, there have now been 24 cases involving human perpetrators in which convictions based on bite-mark analysis have been overturned as a result of DNA analysis. However, not all wrongful convictions based on bite-mark evidence have been voided with many sent for a new trial. Unfortunately, in some cases, the prosecution has had difficulty finding key witnesses or supporting evidence and therefore a new trial has not been initiated. The overturn of these convictions and the criticisms that followed have led to calls to halt the use of bite-marks as evidence until its scientific credibility can be established, and even to recommendations to discontinue altogether the use of bite-mark evidence in criminal investigations in the USA. However, if bite mark analysis can be shown to be a valid forensic technique it has great potential in the judicial system and therefore the author argues that the use of bite mark evidence must not be abandoned, but rather focus on research to determine its validity must be undertaken.

Therefore the aims of this thesis were to address the fundamental limitations of bite-mark analysis as a path forward in establishing the scientific credibility of bite-mark analysis. The four studies conducted in this thesis aimed to estimate the frequency of occurrence of bites, propose the use of 3D imaging technology as an approach to overcome limitations of current methods of bite-mark analysis, investigate the reliability and validity of measurements of landmark dental features made using 3D imaging, and examine the accuracy of matching 3D images of bite-marks to 3D images of candidate dentitions.

The purpose of this chapter is to summarize studies conducted in this research, to highlight the key findings of this research and their significance, and to highlight the implications of the findings from this research. A summary of the four studies are presented below.

6.2 Summary

6.2.1 Study 1

An important first step was to undertake an assessment of the public health implications of dog bites inflicted on humans by estimating the frequency of hospital admissions from dog-bites. Study 1 investigated the annual age- and sex-specific incidence of injuries due to dog bites in Australia during 2001-2013. In Australia, on average, 2061 persons were hospitalized each year for treatment for dog-bite injuries at an annual rate of 12.39 (95% CI 12.25, 12.53) per 100,000 during 2001-2013. The highest annual rates of 25.95 (95% CI 25.16, 26.72) and 18.42 (95% CI 17.75, 19.07) per 100,000 were for age groups 0-4 years and 5-9 years respectively. Rates of recorded events increased over the study period and reached 16.15 (95% CI 15.78, 16.52) per 100,000 during 2011-13. This was the first national study to report the incidence of hospitalization for injuries due to dog-bites for an extended period with complete coverage of all public hospitals in Australian states and territories. The findings add considerably to what is known about the public health problem of dog-bite injuries in Australia. Although the incidence of dog-bites from unidentified dogs is unknown, the findings from this study has indicated that dog-bites are a growing public health problem and it may be important to apply bite-mark analysis in establishing identities of unidentified perpetrating dogs and assist in apprehending them and consequently prevent re-offending.

6.2.2 Study 2

In study 2, the fundamental limitations of bite-mark analysis were discussed with regard to the NAS report. In response to this, recommendations for the use of 3D imaging techniques in bite-mark analysis to address these fundamental limitations of bite-mark analysis were made. The new generation of portable, non-invasive, hand-held intra-oral 3D scanners, that are currently used as an alternative to conventional dental impression materials in clinical dentistry, have made the process of acquiring dental impressions faster and easier. The 3D scanning permits the imaging of bite-marks as well as the imaging of dentitions of suspected perpetrators in 3 dimensions with high resolution, and would allow researchers to compile large databases of virtual images of dentitions of biting animals for quantifying population variation. In addition, 3D scanning would make it feasible to compare a large number of landmark features when matching the scan of a bite-mark to the scan of a candidate dentition. This technology makes it possible to investigate the sources of error and quantify that error, and thereby to take steps to remove or at least reduce error including by limiting subjectivity associated with human judgement.

6.2.3 Study 3

Prior to employing 3D scanning tools that were recommended in study 2 for recording bite-marks and suspect dentitions, the reliability and validity of measurements of landmark dental features, made with an intra-oral 3D scanner had to be investigated. Study 3 discusses the steps involved in assessing the reliability and validity of measurements of landmark dental features made with an intra-oral 3D scanner with a handheld digital caliper as a comparison measure. To investigate the reliability and validity of measurements made with an intra-oral 3D scanner, two raters each measured 84 tooth and 26 arch features of 50 sets of upper and lower human dental casts first using digital hand-held callipers and second using the measuring tool provided with the ZFX IntraScan intra-oral 3D scanner applied to 3D images of the dental casts. The measurements were repeated at least one week later. Reliability and validity of the intra-oral 3D scanner were quantified concurrently by calculation of intra-class correlation coefficients (ICC) and standard errors of measurement (SEM). The measurements of 110 landmark features of human dental casts made using the intra-oral 3D scanner were virtually indistinguishable from measurements of the same features made using conventional hand-held callipers. The difference of means as a percentage of the average of the measurements by each method ranged between 0.030% and 1.134%. The inter-method SEMs ranged between 0.037% and 0.535%, and the inter-method ICCs ranged between 0.904 and 0.999, for both the upper and the lower arches. The inter-rater SEMs were one-half and the intra-method/rater SEMs were one-third of the inter-method values. This study demonstrates that the ZFX Intrascan intra-oral 3D scanner with its virtual on-screen measuring tool is a reliable and valid method for measuring the key features of dental casts. This study demonstrated that the ZFX Intrascan intra-oral 3D scanner with its virtual on-screen measuring tool is a reliable and valid method for measuring the key features of human dental casts.

6.2.4 Study 4

Extending from study 3, the ability of the Zfx IntraScan intra-oral 3D scanner to record impressions made by dentitions was investigated. The 2009 NAS report (1) indicated that to demonstrate the scientific credibility of bite-mark analysis, it was important to report on error rates in matching bite-marks with suspect dentitions and also to investigate whether particular numbers and type of features are required to establish a match between bite-marks and the suspect dentitions. In study 4, the accuracy of matching 3D impressions with 3D images of candidate dog dental arches made using the Zfx IntraScan intra-oral 3D scanner was assessed. Measurements of 79 landmark dental features on each of the 3D images of upper and lower dog dentitions and the 3D images of the impressions of dog dentitions on modelling clay were made using the virtual onscreen measuring tool provided with the intra-oral 3D scanner. On matching all 79 features of the positive images with those of the negative 3D images, there was a 100% accuracy in the matches. When measurements of landmark features of anterior dentitions usually responsible for bite-marks were matched, there was 100% accuracy. On attempting to identify a subset of key features from the 79, it was found that some features contributed to the overall match rate more than the others. A key finding was that it was possible to establish a 100% match by measuring landmark dental features of the anterior dentition commonly responsible for bite-marks by humans. This study demonstrates that the portable intra-oral 3D scanner is a reliable tool that has the potential to measure the impressions of dental features in modelling clay with sufficient accuracy to allow identification of the dentition that made the impression.

6.3 Key research findings

In this research, the author found that dog-bites are a largely unrecognised problem, with individuals aged 0-9 years being the most affected. By conducting a thorough review of the available literature on 3D imaging tools, it is postulated that, by using 3D imaging tools to record bite-marks, some limitations of bite-mark analysis may be addressed. For this purpose, the reliability and validity of a portable, non-invasive intra-oral 3D scanner that may be used to record bite-marks and suspect dentitions was investigated. In the assessment of the reliability and validity of measurements of landmark dental features made with an intra-oral 3D scanner with a handheld digital caliper as a comparison measure, the author found that the measurements made using an intra-oral 3D scanner were reliable and valid when compared with a digital handheld calliper. The author also demonstrated the ability of the intra-oral 3D scanner in scanning and recording dentitions and impressions of dentitions in under 6 minutes. In addition to the large number of landmark dental features (110 in humans and 158 in dogs) that could be measured using 3D images, the author was able to identify a subset of features that contributed more to a match than the other features. By using the intra-oral 3D scanner, the author was able to demonstrate that it was possible to identify and quantify error. It was found that the 3D images of dentitions can be matched with the 3D images of impressions of dog dentitions.

6.4 Significance of this research

All four studies presented in this thesis are novel. The findings from each of the 4 studies in this research program make an important contribution to the establishment of scientific credibility of bite-mark analysis and the applicability of bite-marks as forensic evidence.

The findings from Study 1 have demonstrated the seriousness of dog-bites as a growing public health problem and identified young children as most commonly affected. This study provides the justification required for establishing databases of dog dentitions and their bite-marks that can be consulted during forensic investigations of bite-marks from an unknown perpetrating dog. This study provided the rationale to identify a non-invasive technique that could be used in recording bite-marks and also to conduct further research using that technique in identifying perpetrating dogs through their bite-marks**.** Young children may not be able to recognise the perpetrating dog because of the shock and pain during a biting episode, and it may be critical to identify the perpetrating dog to prevent re-offending.

In study 2, the use of a novel, portable, handheld, non-invasive 3D imaging tool as an approach to address the fundamental limitations of bite-mark analysis has been proposed for the first time. The portability of the 3D scanner has the potential to allow scanning of the bite-marks at the crime scene thereby reducing any potential distortions associated with recording bite-marks using photography or dental impression materials. The non-invasive intra-oral 3D scanner records 3D images of bite-marks without the use of any surface coating powders to enhance details of the surface that is recorded. The 3D scanner permits scanning bite-marks in 3 dimensions as compared to 2D photographic methods. Along with eliminating distortions associated with 2D photographic techniques, the resultant 3D image also permits viewing the bite-mark from several angles, thereby permitting a more thorough examination of the bite-mark. The 3D images allow measurements of a large number of landmark features (110 in humans and 158 in dogs) with the potential to allow measurements of increased number of landmark features.

In study 3, the reliability and validity of a novel, portable, handheld, non-invasive intra-oral 3D scanner has been assessed. This is the first study to have assessed the validity of a portable 3D imaging tool that can be easily transported to the crime scene, and can be easily operated by crime scene examiners without the need to resort to traditional casting techniques. This study also demonstrated the capability of 3D images in allowing measurements of a large number of landmark dental features. The findings from this study will provide forensic investigators and forensic odontologists with the rationale to utilize funds in purchasing portable intra-oral 3D scanners for use in routine forensic casework.

In study 4, a proof-of-concept of matching 3D images of impressions of teeth with 3D images of candidate dog dental arches , with images made using the Zfx IntraScan intra-oral 3D scanner is provided. Using techniques demonstrated in this study, it was possible to accurately match 3D images of impressions of dental arches of dogs to 3D images of candidate dentitions. Apart from permitting the examination of a large number of landmark features, this study also demonstrates that it is possible to identify subsets of features that may contribute more to matching, and that it is possible to quantify error rates in matching 3D images of dental arches with the 3D images of impressions of dental arches. With this proof-of-concept on matching dentitions with impressions of dental arches, sufficient evidence has been provided to pursue further research in matching dentitions with bite-marks.

6.5 Implications of this research

The findings from studies conducted in this thesis contribute significantly to establishing a scientific foundation for bite-mark analysis. This research makes an important contribution to the use of bite-mark analysis as forensic evidence by identifying the extent of the problem, identifying a novel 3D tool as an approach to overcome the fundamental limitations of bite-mark analysis, assessing its reliability, validity and accuracy for use in forensic investigations of bite-marks.

The findings from this research will provide evidence for the development of improved public policy in respect of dog-bites. Although the incidence of dog-bite injuries from unidentified dogs is yet to be determined, this research has provided the evidence required for a push for uniform and more complete surveillance of injuries and hospitalizations due to dog-bites. These findings will provide evidence for the further need for policies on dog ownership, correct identification and management of re-offending dogs.

The 3D scanner provides forensic odontologists with a tool that is capable of recording dentitions swiftly and stored in repositories. This would enable populating and storing large numbers of 3D images of dentitions in repositories, that may be consulted during forensic investigations of bite-marks. These repositories of 3D images of dentitions will have significant research potential including assessing the variability of dental features, that can then be used in determining the uniqueness of dentitions. The 3D images produced by the intra-oral 3D scanner provide forensic odontologists with bite-mark evidence in high resolution, in a format that can be moved in 3D space and that can be magnified to examine selected areas of the dentition to examine features more closely. The 3D images produced by the intra-oral 3D scanner may also be shared amongst forensic odontologists easily if there is a need for second opinion by another forensic odontologist or to allow research collaborations.

The current mood with crime scene investigation is to employ tools and techniques that can be used in the field. The findings from this research provide crime scene examiners and investigators with a non-invasive tool that may be used at the crime scene to record bite-marks swiftly and accurately without the use of any additional powders or coatings to accentuate the surface details. Because the time taken to produce 3D images of bite-marks is minimal, 3D images of bite-marks may be sent to forensic odontologists for examination in a timely manner, particularly from remotely located crime scenes. Because 3D images of bite-marks and suspect dentitions can be made in under 6 minutes, time-related distortions are minimised when scanning is performed without delay. This technique also eliminates the need for the placement of an ABFO NO 2 Scale because the measuring tool provided with the scanner is capable of measuring landmark features reliably and accurately. Also, by using 3D imaging techniques, distortions associated with 2D imaging techniques currently used in recording bite-marks will be eliminated. The intra-oral 3D scanner provides forensic odontologists with the opportunity to observe 3 dimensional changes in bite-marks over time enabling bite-mark examiners to report on the effect of time on the appearance of the bite-marks. This may not have been possible with previously used 2D imaging techniques.

Finally, the findings from this research may be used as justification for the use of intra-oral 3D scanners in hospital emergency departments, by crime scene investigators and emergency services such as paramedics who may be trained to record bite-mark injuries. Training emergency personnel and crime scene investigators in using the intra-oral 3D scanners on the field to record bite-marks will not just provide them with a tool capable of recording bite-mark evidence swiftly without wasting valuable time required in treating the injuries, but will also provide forensic odontologists with high-resolution 3D images of bite-marks that can be investigated with great confidence. Accurate recording of a bite mark by a first responder may have the potential to identify criminal assault cases much earlier as well as recording the evidence as early as possible. The 3D images can be freely shared between forensic odontologists, making it easier to seek a second opinion if required. Because of the ability to move 3D images in 3D space, forensic odontologists will be able to explain the characteristics of the bite-marks and dentitions to the courts, with great ease.

6.6 Importance of retaining bite-mark evidence in courts

DNA analysis has become a favored tool with the judicial system as it has demonstrated the potential to establish the guilt of an individual with high degrees of certainty. The ability of DNA analysis in establishing identities of perpetrators of crimes with high degrees of certainty may have resulted in the overdependence on the science (2), which in turn may have resulted in the languishment of other forensic disciplines (3). It may be safe to speculate that the spectacular success of DNA analysis as forensic evidence has had two flow on effects; a) funding directed away from other forensic disciplines; and b) resulting in an expectation that other disciplines must offer the certainty to the level of DNA. Despite its broad applicability, DNA evidence may be prone to contamination, casework overload and insufficient information about error rates and there may be problems with how evidence was collected and handled in individual cases (4). The Farah Abdul Kadir Jama case (5) is testimony to the fact that DNA analysis is not fool proof and must be applied with great caution and with good understanding of its advantages and limitations. It is not advisable to simply rely on one form of evidence and it is important to use supportive evidence in the form of fingerprints and bite-marks.

Bite-mark evidence has the potential to provide supporting evidence required to build a case and to exclude suspected perpetrators. Bite-mark evidence may be of value in several situations. As examples, when a bite-mark with evidence of crowding of the anterior teeth is examined, individuals with well aligned anterior teeth may be readily excluded. Similarly, when a bite-mark depicting a complete set of anterior teeth is examined, individuals with missing anterior teeth may be excluded. When bite-marks with common distinguishing features are found in several cases but the identity of the perpetrator remains unknown, bite-mark evidence may be used as the linking factor that may provide valuable information on the method of assault by the perpetrators, in turn instigating further investigation. Bite-mark analysis may also provide valuable information on whether the bite-marks are a result of human or non-human perpetrators and avoid unnecessary use of time and finances on identifying a human perpetrator or vice versa as a consequence. The site of the bite-mark may also provide DNA samples that may be examined further.

Sexual assaults and child abuse are an ever growing problem in developing countries and these crimes are considered to be serious and unacceptable to society (6, 7) and bite-mark evidence has the potential to provide vital information in criminal investigations of sexual assault and child abuse (8-10). The frequency of biting episodes has been increasing in the United States of America (11), and in South Africa (12). One of the recent and widely reported case has been of that in India, where bite-marks found on the victim was used as supporting evidence with other forms of evidence to implicate the perpetrators (13, 14). This case demonstrates the value of bite-marks as supportive evidence in courts. The findings from this research have provided investigators with a tool that has the potential to provide additional information in criminal investigations of sexual assault and child abuse.

6.7 Concluding words

Bite-mark evidence may be valuable when it is used as supporting evidence to build a case. Matching DNA from the bite-mark to that of a suspect animal provides the primary evidence required, but DNA evidence is not always available and – even if it is – bite-mark analysis can be valuable as supportive evidence and for narrowing the range of possible culprits from which to seek a sample for DNA analysis. In this thesis, this author proposes the use of intra-oral 3D scanning principally because of its potential for eliminating or quantifying error. The reliability and validity of measurements of human dentitions has been established, and a proof-of-concept of the accuracy of matching bite-marks to dentitions has been provided. A framework for future research has been provided, with recommendations for addressing the other limitations of bite-mark analysis. The purpose of this research was to validate measurements made by a portable, non-invasive intra-oral 3D scanner of dentitions and impressions of dog-dentitions in clay. Digital imaging (2D imaging) will remain of value, with 3D recording adding to the information collected rather than replacing 2D imaging. As a follow up to the research findings presented in this thesis, some future directions on the establishment of databases of scanned images of dentitions of biting animals and the investigation of distortion in bite-marks are presented in Chapter 7 of this thesis.

6.8 References

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Chapter 7: Future directions

This chapter outlines the aims and rationale for a future research project based on the findings presented in this thesis. The global aim of this future research in the application of 3D imaging techniques to the science of matching bite-marks to a candidate dentition is to contribute to the restoration of the probative value of evidence from bite-mark analysis and the recovery of its scientific credibility.

The aim of this proposed research is to demonstrate the use of a portable, lightweight, non-invasive intra-oral 3D scanner to:

(a) commence the compilation of databases of scanned images of dentitions

(b) study distortions in bite-marks under controlled conditions, and

(c) expand the number and range of key features measured and demonstrate the inherent advantages of 3D scanning in minimising and quantifying errors and obviating subjective inputs.

7.1 Background

Legal criticisms of bite-mark analysis and admissibility of bite-mark evidence in courts of law

Bite-mark evidence has been used in legal proceedings since 1692 (1) but, recently, forensic investigation of bite-marks and other pattern-matching disciplines have been subject to substantial criticism in judicial rulings (2, 3) and from judicial review groups (4). In the USA, there have now been 24 cases in which convictions of individuals based on bite-mark analysis have been overturned as a result of DNA evidence (5). This has led to calls for suspension of bite-mark evidence until its scientific credibility can be established (6), and even to recommendations to discontinue the use of bite-mark evidence in criminal investigations in the US (7).

7.1.1 Scientific criticisms of bite-mark analysis

In 2006, the National Academy of Science (NAS) was commissioned by the United States Congress to conduct an enquiry on the existing status of forensic science. Along with cases using evidence from other pattern matching disciplines, the NAS reviewed the cases in which bite-mark evidence had been presented as expert evidence. In its report published in 2009, the NAS identified three fundamental limitations of bite-mark analysis. These were that:

(a) the uniqueness or otherwise of human dentitions was yet to be established,

(b) the capacity of human skin to retain the impression of a dentition was yet to be ascertained, and

(c) the quality, number and type of features required to match a bite-mark to a suspect dentition was yet to be established (8). More broadly, the report was critical of errors arising from procedural flaws including distortions and of the failure to quantify and report them.

7.1.2 Distortions in bite-mark analysis

One of the important factors that affect the appearance of bite-marks is distortion. The process of undergoing deformation without breaking or permanent change is called distortion (9). Bite-marks, unlike tool marks, are made on food or human skin and are subject to changes resulting in distortions (10). Primary distortions occur at the time the bite is inflicted (11) and therefore it may be not be possible to quantify primary distortions, but secondary distortions such as time-related distortions may be quantified. Through this research, inherent errors of measurement as a result of the limitations of measuring instruments, lack of analysis of inter- or intra-examiner error have been addressed, however, time-related distortions are yet to be quantified.

7.1.3 Displacement of skin during the biting episode

Skin is the largest organ of the body and has several functions, one of which is as a physical barrier against trauma. In sexual assaults and child abuse cases, bite-marks are commonly recorded on skin. However, the evaluation of bite marks on skin is made extremely difficult by changes due to the visco-elastic responses of the skin to the stress applied during the biting episode (12). Skin tends to be displaced by the biting force and returns to its original position upon removal of the biting force (12). Very little research has been conducted on quantifying displacement of skin during a biting episode. It may be critical to quantify force related displacement of skin during a biting episode.

7.2 3D scanning as an improvement on current methods of impression-making in analysis of bite-marks

Synthetic poly-ether based materials such as silicon have been used to make impressions of bite-marks (13). These materials undergo structural and chemical changes while setting, however, and may cause drying of the underlying skin or introduce moisture into the skin, thereby altering the appearance of the bite-mark on the impression material. (14). Such casting techniques may also interfere with the clinical management of a bite mark. The most frequent method of recording bite-marks is to use photographs. The problem with analysing bite-marks from photographs is that the process is a 2-dimensional interpretation of 3dimensional information (15), resulting in loss of detail. The 3D scanning methods currently used in clinical dentistry are capable of acquiring dental impressions faster and easier than conventional methods such as impressions and potentially of permitting the imaging of bite-marks as well as the imaging of dentitions of suspected perpetrators in 3 dimensions with high resolution. This would make it it feasible to compare a large number of landmark features when matching the scan of a bite-mark to the scan of a candidate dentition. This technology makes it possible to investigate the sources of error and quantify that error, and thereby to take steps to remove or at least reduce error including by limiting subjectivity associated with human judgement.

7.2.1 Previous studies using the Zfx IntraScan intra-oral 3D scanner

In this thesis, the author demonstrates that the Zfx IntraScan intra-oral 3D scanner is a reliable and valid tool for recording and measuring landmark dental features of human dental casts (16). As a proof-of-concept study, The author assessed the accuracy of matching 3D impressions of dog bite-marks with 3D images of dog dentitions made using the Zfx IntraScan intra-oral 3D scanner (17). The critical next steps are to assess the reliability and validity of the Zfx IntraScan intra-oral 3D scanner in measuring landmark dental features of human teeth, to assess its accuracy in matching 3D impressions of teeth with 3D images of human dentitions and to quantify time-related distortions and force-related displacements in bite-marks.

7.3 Research proposal

This proposed research project will be comprised of five studies. The design of and rationale for each are described below.

1. Establishing a database of measurements of human dentitions

Rationale

Currently there is no repository of information that can be used as a reference system for quantifying population variation in human dentitions. As a first step towards resolving this problem, a database of digital images of 50 human dentitions of known age, sex, height and weight using the intra-oral 3D scanner together with measurements of those dentitions using the reliable and valid method demonstrated in this research will be created (16).

Research questions

To what extent are variations in dental features among humans explained by observable characteristics such as race, age, sex, height and weight.

Study population

The study population consists of dental casts of Australian citizens with fully developed dentitions.

Study sample

Around 50 human skulls will be obtained from the School of Medicine, University of Tasmania, School of Anatomy and Human Physiology at the University of Western Australia, Tasmanian Museum and Art Gallery and Queen Victoria Museum and Art Gallery.

Procedure

After obtaining ethics approval, 3D images of dentitions of each skull will be scanned using an IntraScan intra-oral 3D scanner. The resultant 3D images will be categorised based on the age and sex of the skull.

Measurements

One rater will measure 55 characteristics on each of the upper and lower jaws (110 in total), using digital callipers applied to scanned images of the dentition. The software that accompanies the scanner allows co-ordinate information to be extracted from the scanned images.

Analytic approach

Distances, angles and lengths extracted from scanned images, using the software provided with the intra-oral 3D scanner, will be stored. A regression model will be developed relating each of the 110 measurements to the age, sex, height and weight of each individual. The extent to which variation in dental features is explained will be assessed from percentage of variance explained.

Justification of sample size

The sample of n=50 well-characterised dentitions would allow us to detect correlations of 0.38 or greater with 80% power (two-sided $\alpha = 0.05$). In the previous sample of 50 dentitions of unknown age/sex/height/weight, the crown length of the canines had positive correlations greater than 0.38 with 8 of the other 28 crown lengths (range 0.28,0.63), 4 of the 28 bucco-lingual dimensions (range 0.25,0.40), one of the 28 mesio-distal dimensions (range –0.02,0.46) and none of the maximum (range 0.07,0.17) or minimum (range –0.88,0.18) arch-widths. These mid-sized correlations with an approximate marker of age (crown length of the canines) suggest that there is likely to be adequate power for an analysis of multiple explanatory factors.

2. Quantifying distortions of experimental bite-marks made on pig skin

Rationale

Distortions of the impression of a dentition are a problem for bite-mark analysis. Time-related distortions can be quantified. The Zfx IntraScan intra-oral 3D scanner makes it possible to record sequential 3D images of bite-marks, allowing changes over time to be assessed.

Research question

Do distortions of experimental bite-marks made on pork loin vary systematically with time elapsed since the bite?

Study population

The study population consists of dental casts of Australian citizens with fully developed dentitions.

Study sample

An upper and lower dental cast of an Australian citizen will be randomly selected from a pool of dental casts that meet the selection criteria. Pork loins sourced from the local butchery will be used in the study. Pork loins will be disposed of according to council rules and regulations.

Procedure

3D images of the randomly selected dental cast will be made using the Zfx IntraScan intra-oral 3D scanner. By standardising the biting force using a dental cast holder with a gauge to measure force, experimental bite-marks will be made on 10 pork loins. Bite-marks will be scanned immediately after removing the dental casts from the pig leg. The impression will be subsequently scanned in 5 minute intervals for 60 minutes. This procedure will be repeated for all 10 pork loins. Of the 10 pork loins, 5 will be placed in an outdoor setting with temperature that is monitored through the hour. The other 5 pork loins will be placed in an indoor setting with a standard air conditioning. The standard room temperature at the Menzies Institute for Medical Research where the study will be conducted, is 23 degrees Celcius. The test will be repeated on bite-marks made on a second set of pork loins exposed to varying levels of clothing and on a third set of pork loins that have been immersed under water.

Measurements

Measurements of 22 landmark dental features: 6 crown lengths, 6 mesio-buccal dimensions, 6 bucco-lingual dimensions and 4 arch widths of the anterior biting dentition will be made from all scanned images recorded at specified time intervals.

Analytical approach

A linear mixed regression model will be developed relating each of the 22 measurements at each point in time to the distances, angles and lengths extracted from scanned images using the software provided with the intra-oral 3D scanner. The effect of time and temperature on the change in dimensions of landmark dental features on bite-marks will be assessed.

Justification of sample size

I do not have pilot data with which to ascertain whether the sample of n=120 scanned images of pork loins will provide at least 80% power (two-sided $\alpha = 0.05$), but I can readily increase the number of pork loins if necessary.

3. Quantifying primary distortion during a simulated biting episode

Rationale

Displacement of tissue due to the biting force has rarely been studied. It may be important to quantify variability of displacement of tissue during a biting episode. The force of a bite is not known in real-world practice, but possibly it is predictable from the depth of the bite.

Research Question

Does the displacement of experimental bite-marks made on pork loin vary systematically with the force of the bite, is the depth of the bite predicted by the force, and is the relationship between displacement and force mediated by the depth of the bite?

Study population

The study population consists of dental casts of Australian citizens with fully developed dentitions.

Study sample

An upper and lower dental cast of an Australian citizen will be randomly selected from a pool of dental casts that meet the selection criteria. Pork loins will be sourced from the local butchery will be used in the study. Pork loins will be disposed of according to council rules and regulations.

Procedure

3D images of the randomly selected dental cast will be made using the Zfx IntraScan intra-oral 3D scanner. By standardising the biting force using a dental cast holder with a gauge to measure force, experimental bite-marks will be made perpendicular to the tension lines on 10 pork loins by pressing the dental casts against each of the pork loins for 30 seconds. Displacement of skin under varying bite-force will be quantified from the degree and variability of displacement of the inter-canine distances by scanning the bite-marks at each force. Measurements of the depth of the deepest tooth mark in relation to the surface of the skin will be made with the scanner. The procedure will be repeated with incremental increases of bite-force at 2kgf intervals until a maximum of 43.3kgf – the estimated maximum force that can be exerted by anterior human dentition (18) – is reached. The procedures will be repeated at least a week later using a similar sample as an informal check on the reliability of the testing procedure.

Analytical approach

A linear mixed regression model will be developed relating the measurements of distances, angles and lengths of the inter-canine distance to the measured bite-force. The bite-force is expected to correlate highly with depth of the bite. A mediation analysis will be conducted to establish whether bite-depth is intermediate between bite-force and displacement. The effect of time and temperature on the change in dimensions of landmark dental features on bite-marks will be assessed.

Justification of sample size

For the regression analysis, I do not have pilot data with which to ascertain whether the sample of n=10 pork loins will provide at least 80% power (two-sided α = 0.05), but I can readily expand the number of pork loins if required.

4. Reliability and validity of measurements of human teeth using an intra-oral 3D scanner

Rationale

Human dental anatomy and its surrounding structures are studied for both research and therapeutic purposes. The reliability and validity of measurements of human dental casts (16) made with the Zfx IntraScan intra-oral 3D scanner has been previously studied. The critical next step is to assess the reliability and validity of natural human teeth.

Research question

Does the intra-oral 3D scanner provide measurements of the features of human teeth that are as reliable, or more reliable, than those made by the conventional method (hand held callipers)?

Study population

The study population consists of skulls of Australian citizens with fully developed dentitions.

Study sample

Around 50 skulls will be obtained from the School of Medicine, University of Tasmania, School of Anatomy and Human Physiology at the University of Western Australia, the Tasmanian Museum and Art Gallery in Hobart, Queen Victoria Museum and Art Gallery in Launceston.

Procedure

Two raters will each measure characteristics (distances and angles between and lengths) of landmark features on each of the upper and lower jaws, using (i) hand-held callipers applied to the teeth and (ii) digital callipers applied to scanned images of the teeth made using the intra-oral 3D scanner, and then repeat the measurements at least one-week later.

Measurements

55 characteristics on each of the upper and lower jaws (110 in total). They include 14 tooth crown (maxillary arch), 14 bucco-lingual (maxillary arch), 14 mesio-distal (maxillary arch), 14 tooth crown (mandibular arch), 14 bucco-lingual (mandibular arch), 14 mesio-distal (mandibular arch), 7 minimal arch width (maxillary arch), 6 maximum arch width (maxillary arch), and 7 minimal arch width (mandibular arch) and 6 maximum arch width (mandibular arch) measurements.

Analytic approach

The repeated measurements of distances, angles and lengths made by (i) hand-held callipers applied to the casts, and (ii) digital callipers applied to scanned images of the dentitions, will be assessed for intra-rater and inter-rater reliability and between-method reliability. Statistical methods will include calculation and comparison of means of test-retest, rater-rater and method-method differences, inspection of Bland-Altman plots, regression of differences on covariates for factors that may influence measurement error, and calculation of intra-class correlation coefficients (ICCs) together with standard error of measurement (SEM) using statistical methodology for the concurrent assessment of inter-rater and intra-rater reliability developed by Eliasziw et al (19).

Justification of sample size

Using the tables provided by Walter et al (20), a sample size of 46 would provide 80% power (two-sided $\alpha = 0.05$) to detect an estimated ICC of 0.9 as being different from the benchmark value (0.8). This suggests that the sample of n=50 will provide adequate power.

5. Matching impressions of human dentitions made on clay to their corresponding dental casts

Rationale

Bite-mark analysis is based upon the ability of forensic odontologists to match features of bite-marks to features of suspect dentitions, but the accuracy of such matching is yet to be ascertained. The author has provided proof-of-concept of matching measurements of experimental dog bite-marks made on clay to measurements of dog dentitions (17). A critical next step is to ascertain the accuracy of matching impressions of dentitions to actual human dentitions. Impressions will be made on clay because of its wide availability and its acceptance as a test medium for research on human bite-marks (21).

Research Questions

Does the intra-oral 3D scanner provide reliable measurements of the characteristics of features of experimental human bite-marks on clay? Can these measurements be used to match experimental human bite-marks with suspect dentitions?

Study population

The study population consists skulls of Australian citizens with fully developed dentitions.

Study sample

Around 50 human skulls will be obtained from the School of Medicine, University of Tasmania, School of Anatomy and Human Physiology at the University of Western Australia, Tasmanian Museum and Art Gallery and Queen Victoria Museum and Art Gallery.

Procedure

3D images of human dentitions will be made using the Zfx IntraScan intra-oral 3D scanner. Impressions of human dentitions will be made on clay. These impressions will be scanned immediately to create a 3D image of the impressions of the dentitions.

Measurements

Two raters on two occasions will measure the 55 characteristics of landmark features on each of the upper and lower dentitions using hand-held callipers and digital callipers applied to scanned images of the impressions of the dentitions. The software that accompanies the scanner allows co-ordinate information to be extracted from the scanned image of the impressions of the dentitions to allow measurements of the same 110 characteristics.

Analytic approach

An algorithm based on 110-dimensional Euclidean distance between the distances, angles and lengths of key features of bite-mark and dentition will be used to select the closest match and provide a quantitative measure of the closeness of the match. The overall result of the experiment will be assessed as the overall percentage of successes. The 110 measurements of the impressions and the dentitions that caused them that are made using the software provided with the scanner will be compared as in an inter-method comparison study, which strictly it is not**.**

Justification of sample size

For the proportion of successes from n=50 trials, the lower one-sided 95% confidence limit (exact method) implies lower bounds of 94% if there are 50 successes, 83% if there are 46 successes, and 73% if there are 42 successes. These provide adequate precision particularly because incorrect matches were rare in the proof-of-concept study when more than a small number of features was used in matching. For the method-comparison study, a sample of n=50 is greater than the 46 needed to provide 80% power (two-sided $\alpha = 0.05$).

Finally, this research plan will provide significant benefits in terms of the objectivity and delineation of the appropriate use of bite-mark analysis and the apprehension and prosecution of perpetrators of violent crimes.

7.4 References

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